Spring 5-31-2006

PDA based ambulatory pulse oximeter

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ABSTRACT

PDA BASED AMBULATORY PULSE OXIMETER

by
Arpita Shah

The main aim of the research was to develop an ambulatory pulse oximeter which can be used to monitor the SpO_2, heart rate (HR) and plethsymograph (PPG) waveform of a person. To achieve this, an algorithm was developed in LabVIEW 8.0 to extract the HR, SpO_2 and PPG data from a Nonin Xpod device, Nonin Medical, Inc. LabVIEW PDA software was developed to make it compatible with the PDA. LabVIEW software was also developed for sending the data to the PDA via Bluetooth Pulse Oximeter commercialized by Nonin Medical Company.

Using this algorithm, data was collected from three different sensors, namely finger, ear and reflectance sensor which can be used in many places. All the three sensors were attached each at a time during different activities and movements which included hand movement, vertical and horizontal head movement, twisting, walking and spot jogging. Comparative study of each sensor was made to conclude which sensor was a preferred choice over the other during each activity. Comparative study among the sensors was also done to observe which sensor worked better with HR and SpO_2 monitoring along with motion. Various tests such as supine-stand test and mental activity were performed to observe the changes in the blood flow of a person using the PPG waveform. From the results obtained it was concluded that different sensors were preferred during different movements. For monitoring HR with motion, a reflectance sensor worked better, while the finger sensor for SpO_2 monitoring with motion. Results obtained from the supine stand and mental activity tests were as per the expected results.

PDA BASED AMBULATORY PULSE OXIMETER

by
Arpita Shah

A Thesis
Submitted to the Faculty of
New Jersey Institute of Technology
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Biomedical Engineering

Department of Biomedical Engineering

May 2006

APPROVAL PAGE

PDA BASED AMBULATORY PULSE OXIMETER

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To my parents, Jitendra Shah and Nayana Shah, and my family

for their support throughout the whole thesis tenure.

ACKNOWLEDGMENT

I wish to express my gratitude to those who generously helped me color the mosaic of this thesis with their knowledge, expertise and support.

I would like to begin my acknowledgement by thanking Professor Michael Bergen, my advisor, who has guided me throughout my thesis tenure with his plethora of knowledge and has always motivated me. His valuable and countless resources, insights and support played a major part towards the completion of my thesis.

I would also like to thank Dr. Tara Alvarez, who guided me towards the completion of my thesis. She has not only guided me towards my thesis but also helped me with my graduate studies.

My appreciation to Dr. Mesut Sahin for serving on my thesis committee and for his valuable suggestions.

Thanks to all the members of the Neurobehavioral Research Unit at the Veteran Affairs NJ Health Care System.

I have always had my parents behind me to keep my courage going on and kept saying that nothing is impossible in this world if you wish to achieve it. My sister and brother who would always make me laugh in my bad times to keep me up and going again towards my completion. Thanks to all my friends for their endless support.

Lastly, thanks to my friend Snehal who was always there besides me during my difficult times. He was the one who motivated me to take up thesis at a point where I was confused and scared on taking it up. It's because of him that I am at a point where I can be proud of the completion of my thesis.

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CHAPTER 1

INTRODUCTION

1.1 Objective

The aim of this research was to develop an ambulatory pulse oximeter that can monitor the patients SpO_2, heart rate and also display the plethysmograph (PPG) waveform that provides the blood flow information of the patient at a particular site. PDA is the instrument used to display all of this information and a 24 hour display is possible.

A software program was developed using Laboratory Virtual Instrument Engineering Workbench (LabVIEW) for displaying the SpO_2, heart rate and the PPG waveform. LabVIEW PDA program was used for data acquisition and analysis of the pulse oximeter data using a Personal Device Assistant (PDA). LabVIEW software was also developed for sending the data to the PDA via Bluetooth Pulse Oximeter commercialized by Nonin Medical Company.

Pilot data were collected and analyzed to test the software of the PDA based Ambulatory Pulse Oximeter system. A comparative study of the various probes; finger, ear and reflectance were done for the following conditions: hand movement, head movement, twisting, walking and spot jogging. Analysis of data was used to compare probes and determine which had better performance during each movement. Sensors were compared for heart rate and SpO_2 analysis with motion. Several tests such as supine-stand test, and mental activity were conducted to observe the variation in the blood flow. It was concluded that with motion as well as for SpO_2 analysis with motion, ear sensor was the best choice and reflectance sensor (RS) for HR monitoring with motion.

1.2 Background Research

There are many conditions where it would be useful to measure a person's oxygen saturation level. When a person is being carried in an ambulance while being transported to the hospital after a cardiac episode, it is important to monitor the oxygen level of the patient. When anesthesia is being administered, it is also important for a physician to measure the oxygen level to prevent any casualty. Oxygen level monitoring is also required during post-recovery of the patient. Even with neonates, a pulse oximeter is able to monitor the oxygen level without much discomfort to the newborn. A pulse oximeter being non-invasive and capable of measuring many physiological parameters has many advantages over other systems. They are now a standard part of preoperative monitoring which gives the operator a non-invasive indication of the patient's cardio-respiratory status. It is also used for detecting hypoxia before a patient becomes cyanotic. Mountain climbers also find monitoring their oxygen level useful. Due to all these reasons it is now considered the 'fifth' vital sign, the other four being temperature, heart rate, blood pressure and respiratory rate [1].

Figure 1.1 The Five Vital Signs [20].

1.2.1 Underlying Theories of Pulse Oximeter

This section focuses on the theories behind a pulse oximeter and the physiology of the blood gas transport.

1.2.1.1 Pulse Oximeter. Pulse oximetry is a simple, non-invasive method to monitor the percentage of hemoglobin which is saturated with oxygen. Oxygen saturation basically measures the degree of the hemoglobin (Hb) in red cells that is saturated with oxygen. Oxygen carried in the bloodstream is mainly bound to hemoglobin. One molecule of hemoglobin can carry up to four molecules of oxygen, which is then 100% saturated with oxygen [2]. The normal value of oxygen saturation (SpO_2) is above 97%. The pulse oximeter is based upon the principle of Beer Lambert's Law which relates the concentration of oxygen in the blood to the amount of light absorbed when transmitted through the blood. Pulse oximetry use pulses of light at two different frequencies to probe the blood in the capillaries of the skin. The amount of light absorbed at each frequency is recorded and compared to compute the oxygen saturation (SpO_2). This measurement is directly correlated to the partial pressure of oxygen in hemoglobin (SaO_2) which determines how well oxygen is delivered to cell tissues in the body.

1.2.1.2 Physiology of Oxygen Transport

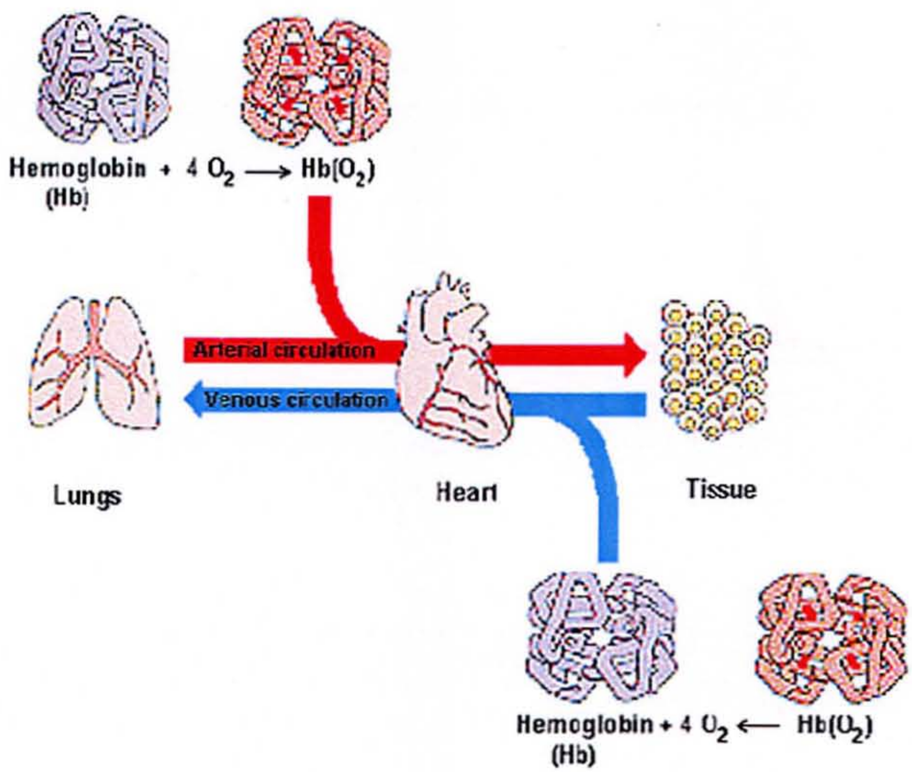


Figure 1.2 Role of hemoglobin in oxygen transport [4].

The oxygenation and deoxygenation of the blood occurs during each breath where approximately 20% of air is oxygen. This oxygen is transported to the lungs. It is then exchanged across a membrane into oxygen depleted hemoglobin in the red blood cells. The oxygenated hemoglobin flows through the arterial system to the heart where it is distributed throughout the body to the tissues [4]. Cells in the tissue metabolize the oxygen releasing carbon dioxide. CO_2 is then transported back to the lungs through the veins and diffuses from the blood into the lungs. Hypoxia occurs when someone lacks oxygen and there are various types of hypoxia based on the oxygen levels.

1.2.2 Physiology of Tissue Respiration

The skin consists of many layers of different types of cells. The outer surface of the skin, known as the epidermis, consists of four layers. The outer layer–the stratum corneum–is composed of flattened cells lacking nuclei and forms the protective layer for the body. The other three layers in the epidermis are composed of proteins, lipids, and pigment or melanin. The epidermis is approximately 0.1 to 0.2 mm thick [5]. Underneath the epidermis is the corium which is composed of connective tissue containing lymphatic's, nerves, nerve endings, a system of capillaries, sebaceous and sweat glands, and elastic fibers. Blood flows from the lower dermis to the upper dermis and returns by means of capillaries which are arranged in vertical loops approximately 0.2 − 0.4 mm in height [5].

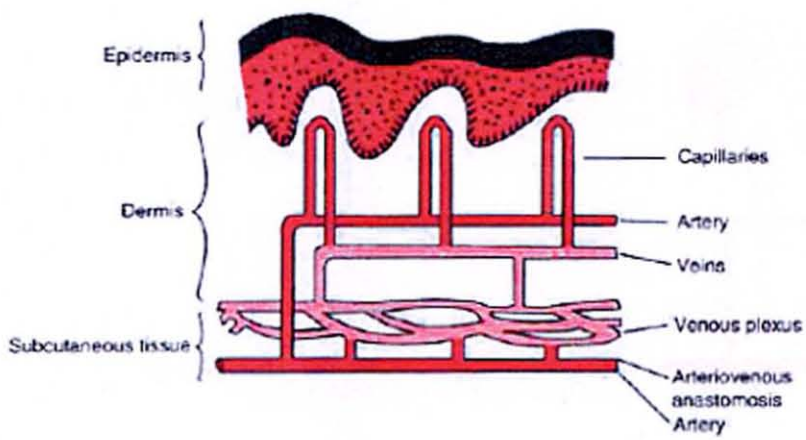


Figure 1.3 Skin Circulation [13].

Gas exchange in tissue occurs in the same fashion as gas exchange in the lungs i.e., by diffusion. The partial pressures of oxygen and carbon dioxide in tissue are different compared to the lungs and are proportional to the metabolism in that area. The rate of respiration depends on the partial pressure gradient, the surface area of the capillaries, the length of the diffusion path, and the amount of diffusion resistance that the molecules experiences passing through various structures [6].

1.2.3 Principles and Calculations of Pulse Oximeter

Functional arterial oxygen saturation (SaO_2) is defined as "the ratio of HbO_2 to the total amount of arterial Hb available for reversible oxygen binding" [6]. When measured using pulse oximetry, this ratio is defined:

$$SpO2 = \frac{HbO2}{HbO2 + Hb}$$

The red color of blood results from the relatively strong absorption of the short light wavelengths by the Hb and HbO_2 molecules. Oxygenated hemoglobin (HbO_2) absorbs light in the near infrared light spectrum and the deoxygenated or reduced hemoglobin (RHb) absorbs light in the red spectrum. The difference in color of RHb and HbO_2 molecules is the key to pulse oximetry.

Pulse oximetry depends on the spectral analysis for measurement of oxygen saturation; i.e., the detection and quantification of components in solution by their unique light absorption characteristics. The pulse oximeter combines the two technologies of spectrophotometry (which measures hemoglobin oxygen saturation) and optical plethysmography (which measures pulsatile changes in arterial blood volume at sensor site). Detection of the oxygen saturation of hemoglobin is based on Beer Lambert's law which states that the amount of the substance can be calculated with the help of the intensity of light transmitted through a solution. So depending on the intensity of the light transmitted to that reflected, gives the concentration of the substance [7].

Beer lamberts Law states:

$$I = Io\ e^{-xcl}$$

Where I= Intensity of light transmitted

Io= Intensity of light reflected

x= extinction coefficient of the solute (a constant for a given solute at a specified wavelength)

c= concentration of solute (hemoglobin)

l= path length the light is transmitted through the liquid

Taking the log of transmitted intensity of light over the reflected intensity of light results in:

$$\ln (I/Io) = -xcl = R$$

where A is the absorbance or the optical density.

The absorbance of different wavelengths is dependant on the different concentrations of reduced and oxygenated hemoglobin, and is detected by transmitting light of specific wavelengths across the hemoglobin and measuring the intensity on the other side [7]. The amount of light absorption at each frequency depends upon the degree of oxygenation of hemoglobin within the tissues.

Basic pulse oximetry involves transmitting lights of two wavelengths through a blood sample of known length which contains both oxygenated as well as reduced hemoglobin, recording the reflected light and then taking the ratio of the red light to that of the infrared light. The two different wavelengths of light used must be such that each will preferentially absorb one of them. This is true of hemoglobin, which has peak absorption of reduced hemoglobin at 660nm (red light), and oxygenated hemoglobin at 940nm (near infrared light). This can be seen in the diagram below.

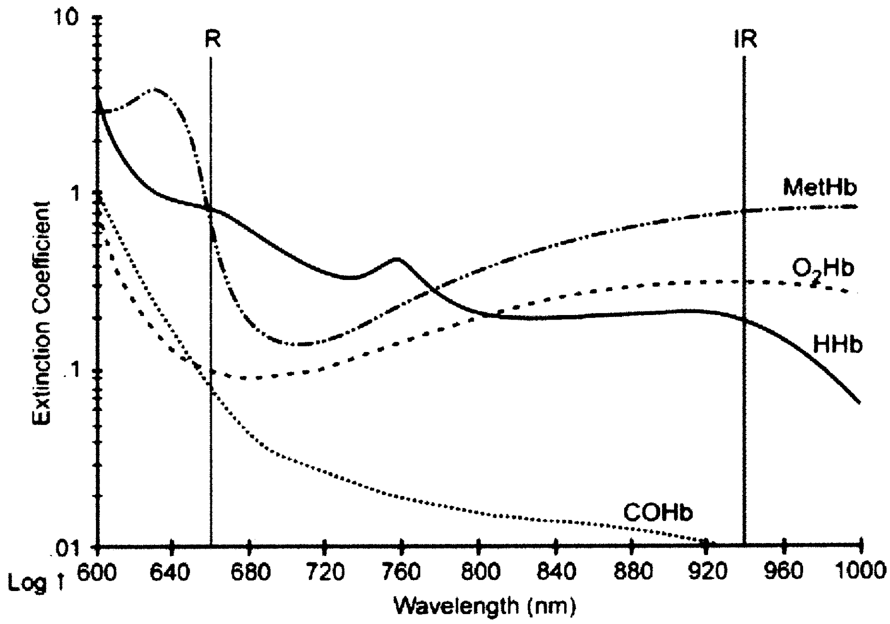


Figure 1.4 Extinction curves of reduced hemoglobin, oxyhemoglobin, methemoglobin and carboxyhemoglobin [21].

Methemoglobin absorbs light at both wavelengths to an equal extent; the absorption of red light by carboxyhemoglobin is similar to oxyhemoglobin [7]. The relationship between each pulse and the light measured by a pulse oximeter is depicted in Figure 1.5. Note that the amplitude optical pulse received by the sensor decreases for each pulse. However, because it is more logical to think of heart beats as making peaks instead of valleys, this signal is usually inverted when displayed on a pulse oximeter output. Also note the slight delay between the QRS complex and the optical pulse. This occurs from the time it takes for the pulse to travel from the heart to where ever the pulse oximeter is placed (forehead, finger, etc.).

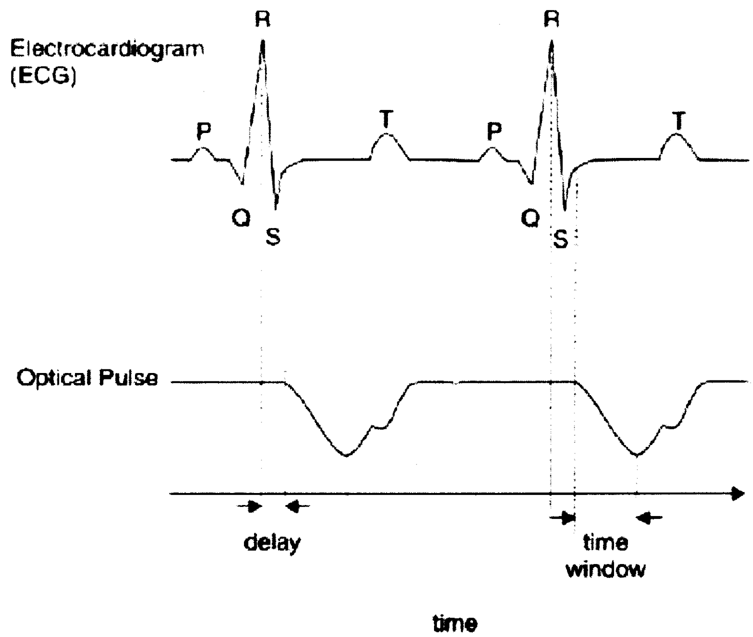


Figure 1.5 Relation of PPG and QRS complex [13].

However, red light is absorbed more by Hb than HbO_2. Skin pigment, bones, and arterial and venous blood are the major absorbers. In addition, light is scattered in many directions as it enters the skin. Thus, light received by the photodetectors rarely travels in a straight path and it is heavily attenuated [6]. In determining SpO_2, interest is in the oxygen saturation of the arterial blood. The system needs to isolate absorbance of arterial blood from venous blood, connective tissue and other extraneous matter. This can be accomplished easily as arterial blood is pulsatile unlike other tissue. Thus, the pulse added signal can be distinguished from nonpulsatile signal by filtering the extraneous noise [7].

This is achieved by the DSP unit of the pulse oximeter. The microprocessor or the DSP unit can distinguish the absorbance of the pulsatile fraction of the blood i.e., that due to arterial blood (AC), from the constant absorbance by nonpulsatile venous or capillary blood and other tissue pigments (DC), thus eliminating the effect of tissue absorbance to measure the oxygen saturation of arterial. The AC and DC components of the light absorbance are depicted in Figure 1.6.

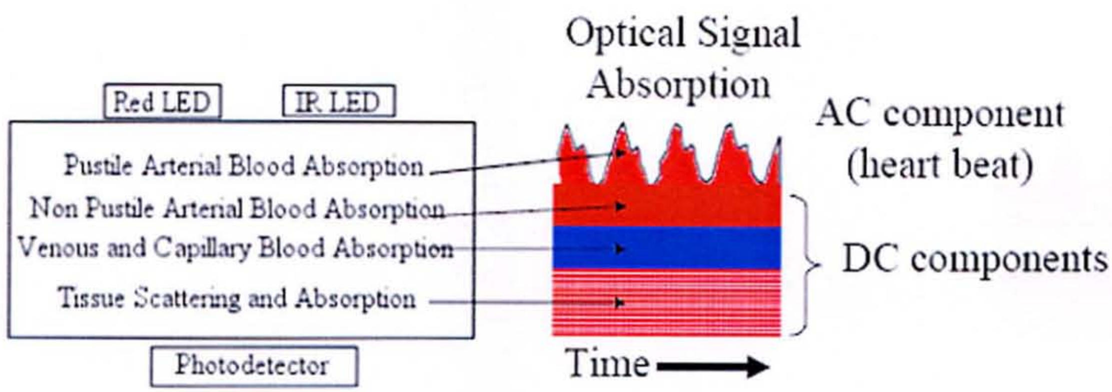


Figure 1.6 Pulsatile (AC) and non pulsatile (DC) components of blood [4].

The pulsatile expansion of the arteriolar bed produces an increase in path length thereby increasing the absorbance. All pulse oximeters assume that the only pulsatile absorbance between the light source and the photodetectors is that of arterial blood. The microprocessor first determines the AC component of absorbance at each wavelength and divides this by the corresponding DC component. From the proportions of light absorbed by each component at the two frequencies, the microprocessor then calculates the ratio (R) of the "pulse-added" absorbance [7].

$$R = \frac{ACred/\,DCred}{ACired\,/\,DCired}$$

Within the oximeter memory there is a series of oxygen saturation values obtained from experiments in which human volunteers were given increasingly hypoxic mixtures to breathe, until saturation values of 80% were obtained [7]. R is compared with the stored values and the oxygen saturation is displayed.

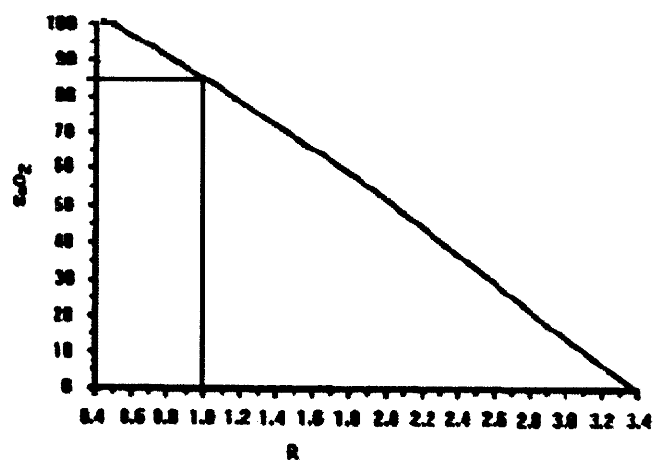


Figure 1.7 R vs. SaO_2 curve [13].

A typical empiric linear approximation to the R vs. SaO_2 curve is [8]:

$$SpO_2 = 110 - 25R$$

1.2.4 Probes

Most pulse oximeters are purchased with a standard reusable finger-clip probe, although disposable finger probes are available. Several other probes are available such as ear-lobe, toe, nose and forehead dependent on the application. Probes are also available for neonates, children and adults. The accuracy of these probes is dependent on the type and site of location of probe.

The technology used for a finger and an ear probe transmissive, one in which the source and the photodetector are on the opposite sides of the tissue.

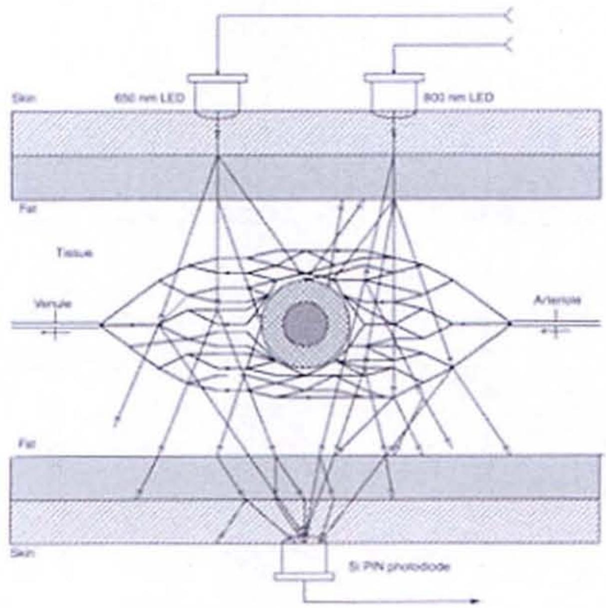


Figure 1.8 Transmissive type of sensor [17].

The other type of probe which is finding lots of importance is the reflective type as it can be applied on various body sites. With this type of probe, the source as well the photodetector is on the same side.

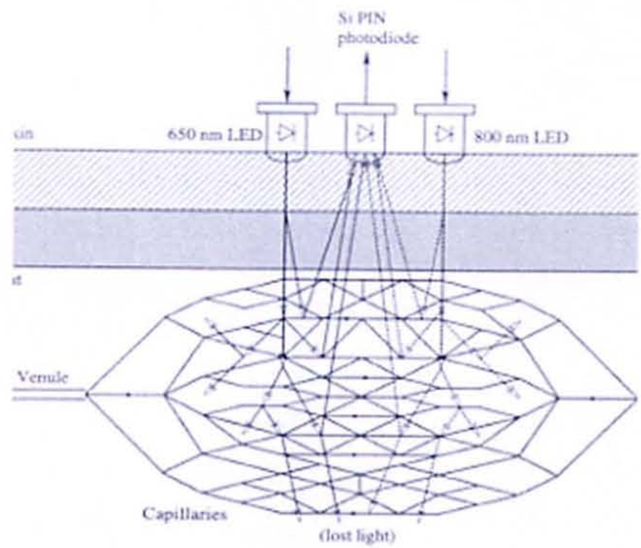


Figure 1.9 Reflective type sensor [17].

1.2.5 Heart Rate, Blood Pressure, Plethysmographic Waveform

1.2.5.1 Heart Rate. Heart rate is a term used to describe the frequency of the cardiac cycle. It is considered one of the four vital signs. Usually it is calculated as the number of contractions (heart beats) of the heart in one minute and expressed as "beats per minute". The heart beats about 60 to 80 times a minute on average for humans at rest [9]. Resting heart rate usually increases with age, and it is generally lower in physically active people. Cardiac output of a person can change with exercise or any physical activity and thus increasing the heart rate from the resting state.

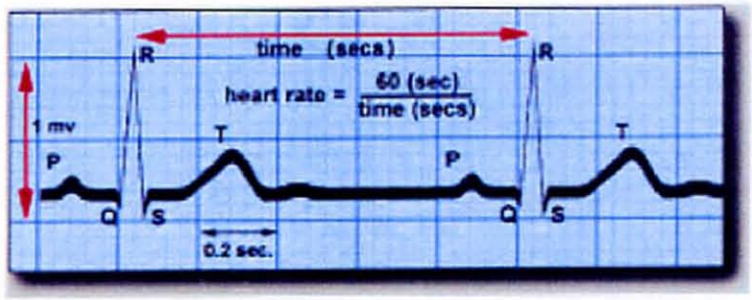


Figure 1.10 Heart rate Calculation [10].

1.2.5.2 Blood Pressure. Blood pressure is the force of blood against the walls of arteries. Blood pressure is recorded as two numbers: the systolic pressure (as the heart beats) over the diastolic pressure (as the heart relaxes between beats). Blood pressure is measured in millimeters of mercury (mmHg) and recorded as two numbers systolic pressure "over" diastolic pressure. Systolic blood pressure represents the maximum pressure exerted when the heart contracts. If the pressure is high, the heart must work harder to maintain adequate blood flow to the body. Blood pressure changes depending on posture, emotional state, temperature, exercise etc. Normal blood pressure is less than 120 mmHg systolic and less than 80 mmHg diastolic [10].

1.2.5.3 Plethysmographic Waveform. The plethysmographic waveform correlates to the flow of the blood at the sensor site. The pulse amplitude of a PPG waveform is relative to the blood flow at that particular site. The pulse amplitude is small during low peripheral perfusion. The magnitude of pulse of the plethysmograph waveform changes depending on the peripheral resistance of the sensor site. If a person has blood vessels of small radius they have high peripheral resistance and thus have small pulse amplitudes. The height of the pulsatile component of the PPG provides the difference of the systolic and the diastolic pressure. In each pulse, there is a main pulse as the blood flow increases sharply with the ejection of blood from the left ventricle. Sometimes there is also a minor pulse riding on the end of the main pulse known as the dicrotic wave. The dicrotic wave results from a combination of the aortic valve closure and a reflected wave from the upper or lower body.

a.) PPG pulse with dicroic wave   b.) PPG pulse without dicroic wave

Figure 1.11 Different types of PPG waveform [13].

The three main applications for PPG are: pulse waveform analysis, segmental arterial systolic pressures, and pulse volume changes.

1.2.6 Ambulatory Monitoring

Ambulatory monitoring has become a need for most of the physicians today. It plays a vital role in today's life. It deals with the measurement of the cardiac and physical disorders during daily activity. There are advantages towards ambulatory monitoring over the clinical or laboratory monitoring. In laboratory monitoring, the patient is forced not to move and to stay on the bed for hours to sometimes days, which makes the patient feel uncomfortable, whereas ambulatory monitoring the patient/ subject can move and do his/her day to day activities. During laboratory monitoring, the patient may become nervous due to the environment around him/ her. While using ambulatory monitoring, it is also possible to record all possible reactions and emotions of the patient. Ambulatory monitoring also helps the researcher get a better understanding of the patient's symptoms plus it helps in taking repeated recordings without the need for an observer. Ambulatory monitoring improves the precision of measurement by taking numerous readings, average daytime, nighttime and 24 hour may then be calculated. The disadvantage of ambulatory monitoring is that it is expensive. Most of the ambulatory monitoring is done using a PDA. LabVIEW software can be incorporated into the PDA.

1.2.7 Introduction to LabVIEW

Laboratory Virtual Instrument Workbench (LabVIEW) is an industry-leading software tool for designing test, measurement, and control systems. It is developed by National Instruments (Austin, Texas). LabVIEW 8.0 was used for this project. LabVIEW graphical development has revolutionized the way thousands of engineers and scientists work, providing improved product quality, shorter time to market, and greater engineering and manufacturing efficiency [12]. With LabVIEW, it is easy to analyze the data and interface with real world signals. The LabVIEW programs are called Virtual Instruments (VI's) as they imitate the actual instrumentation of the instruments. The main base of LabVIEW is Visual C++ (VC++). It is with the help of VC++, that LabVIEW is more user friendly.

There are two basic components of LabVIEW: front panel and the block diagram. The front panel is similar to any graphical user interface (GUI) of any language program. It consists of the knobs, led display, waveforms etc. The displays can be user controlled or may be already a constant value, depending on the need of the system.

The block diagram appears as a circuit diagram of the instrument. The block diagram is the VI's source code constructed in the programming language G. It consists of the main blocks needed for the software to work as per the system needs. The flow of the data in the block diagram is from the left to right. It includes the data acquisition blocks for reading the data from the device attached to it. The function palette consists of all the functions used to program the VI's. It also has blocks which can be used to store the data in any type of file such as excel, notepad etc. Due to its user friendly quality and its good data acquisition ability, it has been widely used in laboratories and in the industries [10].

1.2.8 Personal Digital Assistant (PDA)

The personal digital assistant (PDA) is a small hand held computer. It is capable of handling many things such as downloaded emails, music files and can run many applications. Some PDAs have wireless capabilities to the Internet. Some PDAs also have global positioning devices to assist with road map directions. PDAs are also able to exchange information with full sized computers. A Pocket PC is a PDA that can do a lot of things that a computer can do, but it is in a condensed version.

There are many other types of PDA's available in the market now. All these PDA's basically have one thing in common: they are designed to complement a desktop or laptop computer, not replace one. Unlike a desktop computer, the PDA does not have a hard drive. It stores basic programs in the ROM, which remains intact even when the machine shuts down. The data and any programs added later are stored in the device (RAM). All PDAs use solid-state memory; some use static RAM and some use flash memory. Short-range wireless connectivity using Infrared (IR) or Bluetooth technology IR is found on most PDAs [11].

PDA's usually come with 2MB minimum of memory. One megabyte of memory can store up to 4,000 addresses and 100 email messages. However, application programs use memory space, so more advanced models usually have more memory (128 to 256 MB). Windows CE operating system takes more memory space so PDAs with this operating system usually have 16 or 32 MB. In some PDA models, the amount of memory is upgradeable to 1GB. Synchronization software on the PDA works with companion software that you install on your PC. Microsoft Pocket PC devices use ActiveSync and Palm OS devices use HotSync synchronization software [11].

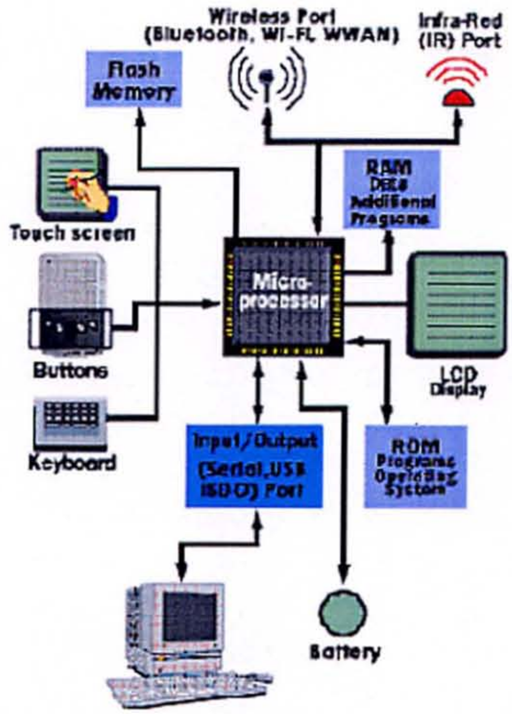


Figure 1.12 Block Diagram of a PDA [11].

The model used in the current study is an Hp iPAQ Pocket PC 5550.

1.2.9 Bluetooth Technology

The art of connecting things is becoming more and more complex every day. One such method is the Bluetooth technology. A Bluetooth connection is wireless and automatic, and it has a number of interesting features. Bluetooth takes small-area networking to the next level by removing the need for user intervention and keeping transmission power extremely low to save battery power.

Bluetooth is essentially a networking standard that works at two levels:

i. It provides agreement at the physical level - Bluetooth is a radio-frequency standard.

ii. It provides agreement at the protocol level, where products have to agree on when bits are sent, how many will be sent at a time, and how the parties in a conversation can be sure that the message received is the same as the message sent.

Bluetooth networking transmits data via low-power radio waves. It communicates on a frequency of 2.45 gigahertz (actually between 2.402 GHz and 2.480 GHz, to be exact). This frequency band has been set aside by international agreement for the use of industrial, scientific and medical devices (ISM) [11].

CHAPTER 2

HARDWARE AND SOFTWARE DESCRIPTION

2.1 Hardware

2.1.1 Xpod Pulse Oximeter

The Hardware consists of an Xpod Pulse Oximeter from Nonin Medical, Inc. It is an OEM product and it allows the user to add an oximetry sensor option externally. This product has simple integration with a 3 wire interface and a serial (RS232) output which helps connect it to the computer ports. It also draws less power of 60mW. It is cost effective and an easy plug and play device. This Xpod generates data packets of 5 bytes 75 times a second. It thus samples data at 75 Hz.

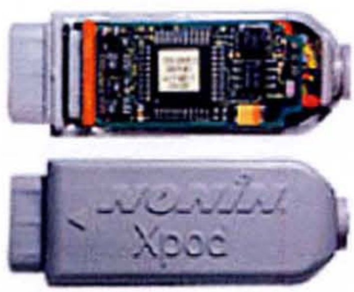


Figure 2.1 Nonin Xpod Pulse Oximeter [18].

The Xpod is connected to a sensor which includes a finger, ear and reflectance. Each sensor is reusable. The finger and the ear sensor use the transmittance technology where as the reflectance one uses the reflectance technology. They have quick and easy application and are also durable and cost effective. It also consists of a 9V battery which provides the power to the sensors. This 9V battery is stepped down to 5V by the Xpod to the sensor.

2.1.2 Sensors

2.1.2.1 Finger Sensor.

Figure 2.2 Finger Sensor [18].

Specifications: 1) It has a patient range of 66lbs and greater.

2) Its preferred application is the index or middle or ring finger.

2.1.2.2 Ear Sensor.

Figure 2.3 Ear Sensor [18].

Specifications: 1) It has patient range of 66lbs and greater.

2) Its preferred application is the ear lobe.

2.1.2.3 Reflectance Sensor.

Figure 2.4 Reflectance Sensor [18].

Specifications: 1) It has patient range of 66lbs and greater.

2) Its preferred application is the middle forehead.

2.1.3 Data Format

The device sends the data in 2 forms, data format 1 and data format 2. Ithave used the data format 2 in which 5 bytes of data are sent 75 times a second. The serial format of the data uses 9600 as its baud rate. It uses 8 data bits and has 1 stop bit.

The 5 bytes of data consists of:

Byte 1: being the sync character and this byte is sent 75 times a second.

Byte 2: being the status byte in which if the bit0 of byte 2 is 1 then starting from that frame the HR and the SpO2 data is collected. It is also sent 75 times a second.

Byte 3: being the PPG data which is also sent 75 times a second.

Byte 4: this byte consists of the HR and the SpO2 value.

Byte 5: checksum byte = byte 1+ byte 2+ byte 3+ byte 4.

2.1.4 Bluetooth Enabled Digital Pulse Oximeter

The Bluetooth pulse oximeter uses the Bluetooth technology for transmitting data to the PDA. The key factor towards this device is 30+ foot range from the host to the patient. It also has 120 hours of battery life.

Figure 2.5 Bluetooth Pulse Oximeter [18].

The Bluetooth module is connected to the finger sensor which is similar to the one used with the Xpod Pulse Oximeter and also sends the data in the same format as the Xpod.

2.2 Software

2.2.1 Introduction to LabVIEW PDA

Another major part of this thesis was to write a custom program using LabVIEW 8.0 PDA for data acquisition and analysis. The National Instruments LabVIEW PDA Module extends LabVIEW development for PDA applications. The program was developed in LabVIEW and could easily be transferred to PDA modules. The LabVIEW PDA module modifies the software which makes it more flexible and powerful. The LabVIEW PDA Module is an additional package to LabVIEW that allows software development of applications that run in PDA devices. The PDA module extends the capabilities of LabVIEW to allow building VIs on the host computer, and then compiling and running the VI on the palm OS or Pocket PC device. Initially, the application would be developed using LabVIEW on a host computer. The VI would then be formatted for the PDA and downloaded to the PDA device to run the application. PDA VIs are complied versions of the VIs that can be run on a PDA device. Each PDA VI has a corresponding host VI which is the VI on the host computer. It has a front panel but the PDA does not provide information about the block diagram of the VI unlike the host computer.

2.2.2 Serial Plug-on Device (POD)

The Xpod provides a serial output. A newly available PDA accessory which is used now is a serial pod. The Serial POD adds an external serial device and charging point to the PDA. The serial POD only works with newer model HP iPAQs which have the standard 22 pin connector on the bottom. Null modem style serial devices can be connected to the PDA through the DB9 serial connection on the POD. The POD can also be used to sync the PDA when used with a null modem adapter. A 4mm power jack is incorporated into the POD so that the PDA may be charged using the standard HP iPAQ AC adapter. The connections are fully protected from the environment and an integrated cap can be used to cover the connections when they are not in use.

Figure 2.6 Serial POD [19].

2.2.3 iPAQ

The iPAQ hp Pocket PC is used for analysis and data storage of the pulse oximeter data. It has RAM size of 128MB and ROM size of 48MB and provides full PDA functionality with color displays and integrated connectivity options. It supports Bluetooth and runs on windows CE 4.2 OS. The PDA has a battery life of 24 hours.

Figure 2.7 iPAQ Pocket PC [10].

2.2.4 Software Development of Xpod Pulse Oximeter

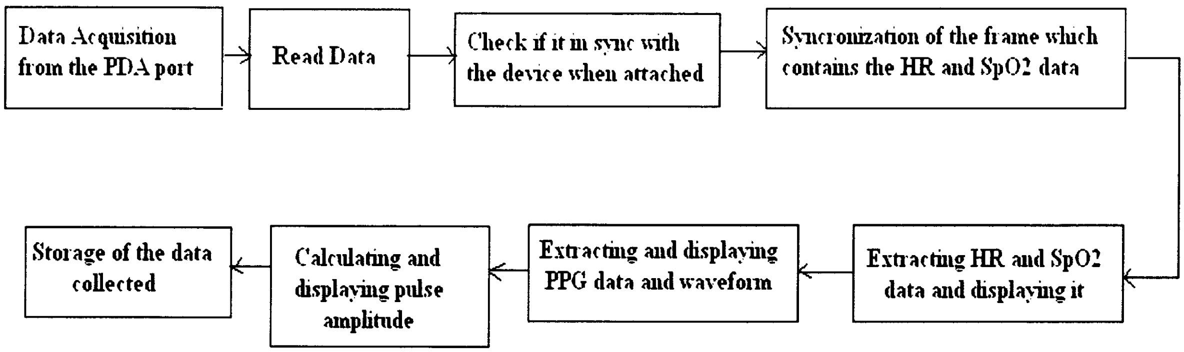


Figure 2.8 Block Diagram of the algorithm used.

The LabVIEW PDA program is designed to first acquire the data from the Xpod. The device sends the data serially and is then sent to the PDA using the serial POD. The first stage of the program includes the serial acquisition blocks with the serial configuration of 9600 baud rate, 8 data bits and 1 stop bit. It also includes the information of the port number of the PDA; in this case it is port number 0. The port numbers in the PDA are one less than the actual port numbers. The port number 1 of the PDA says "serial cable on COM1."

The data at the port are then read at the rate of 375 bytes per second, which is 5 bytes of data 75 times a second. It is now checked if it is in sync with the device. To verify if it is in sync, the following formula is used. If byte1=1 and byte2> 127 and byte4<128 then the data acquisition is said to be in sync. If these conditions are not met the data are deleted and the next 375 bytes are taken from the buffer at the port. Once these conditions are met the data are further passed to extract the heart rate and the SpO_2 values. Byte 4 contains the heart rate and the SpO_2 information. Byte 4 also contains undefined values and the other data such as the extended heart rate and SpO_2 or the averaged heart rate and SpO_2. The data are sent in such format that when bit 0 of byte 2 is 1 i.e., when byte 2 is 129 in decimal the byte 4 contains the MSB of the heart rate value. The frame just after that in byte 4 contains the LSB value of the heart rate. Thus the program was made such that it first searches for 129 in the entire byte 2 columns and as soon as the bit 0 of byte 2 is 1, it extracts the byte 4 value of that corresponding frame and then goes to the next frame and extracts the LSB value from byte 4.

For calculating the heart rate the formula used was:

$$HR = HR\text{-}MSB * 128 + HR\text{-}LSB.$$

This formula calculated the HR every time the data were collected and displayed it on the front panel.

The frame after the heart rate LSB value consisted of the SpO_2 data. Similarly, the decimal 129 is searched in the byte 2 column and array subset block is used which takes in the data of length 3 from the byte 4 column and then extracts the third value from byte 4 after the 129 decimal from byte 2. This is also done when each data enters the port. The value is then displayed on the front panel. An example of the data which are saved is shown below to explain the whole concept easily.

Table 2.1 Data Format

BYTE1	BYTE2	BYTE3	BYTE4	BYTE5		
1	128	90	0	219		
1	128	91	0	220		
1	128	91	0	220		
1	128	92	0	221		
1	128	92	0	221		
1	128	93	0	222		
1	128	93	0	222		
1	128	93	0	222		
1	128	93	0	222		
1	129	93	0	223	HR-MSB	Calculated HR
1	128	92	75	40	HR-LSB	75
1	128	92	99	64	SpO2	
1	128	93	14	236	Software Revision Level	
1	128	96	0	225		
1	128	101	0	230		
1	128	107	0	236		
1	128	115	0	244		
1	128	123	0	252		
1	134	129	99	107	SpO2 Slew	
1	134	133	98	110	SpO2 B-B	
1	134	135	0	14		
1	134	134	0	13		
1	134	131	0	10	Extended HR-MSB	
1	134	127	75	81	Extended HR-LSB	
1	134	123	99	101	Extended SpO2	
1	134	120	0	255		
1	134	116	0	251		
1	134	114	0	249		
1	128	112	0	241		
1	128	111	0	240		
1	128	110	0	239		
1	128	109	0	238		
1	128	108	0	237		
1	128	107	0	236		
1	129	106	0	236		
1	128	105	75	53		
1	128	104	99	76		
1	128	104	14	247		
1	128	105	0	234		
1	128	105	0	234		

The PPG data are also extracted from the incoming data. From the 5 bytes of data, the 3rd byte contains the PPG data. So to do this an array is created which contains this data from the incoming data. The values are then used to display the PPG waveform on the front panel. Pulse Amplitude is calculated from the data of the PPG. The maximum point and the minimum point of the pulse is measured to quantify the pulse amplitude. Each time the data are received the value of the maximum and the minimum pulse is quantified. From the array of the data, the maximum and the minimum values are searched and then the minimum value is subtracted from the maximum one which quantifying the pulse height. It is then displayed on the front panel which is relative to the blood flow at that particular site where the senor is applied. This is done real time. Block Diagram where all the calculations are done can be seen in the Appendix B. The block diagram includes the configuration part of the serial port. The configuration section includes the information on the baud rate, the data bits, the parity and stop bits.

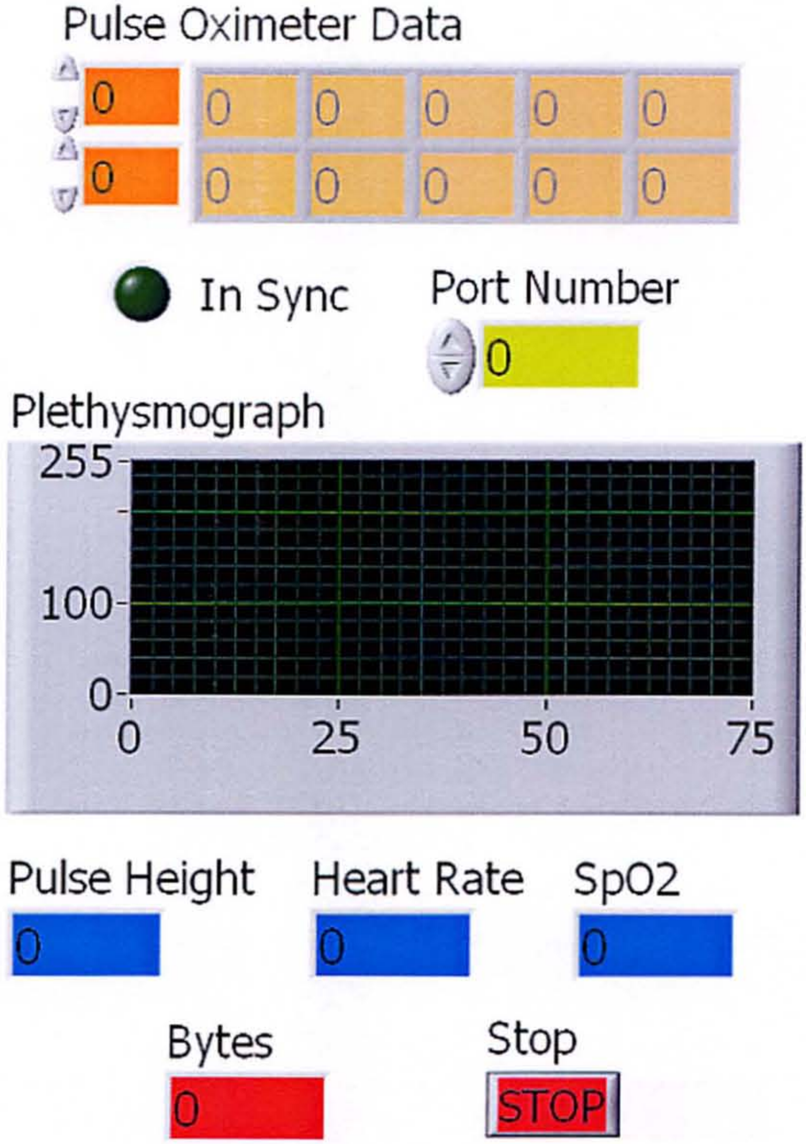


Figure 2.9 Front panel of Xpod Pulse Oximeter.

Front Panel of the LabVIEW program is shown in Figure 2.9. The front panel displays the calculated heart rate, SpO_2 and the pulse height. The port number indicator displays the port of the PDA which receives the data. The graph displays the plethysmograph waveform.

2.2.5 Software Development of Bluetooth Pulse Oximeter

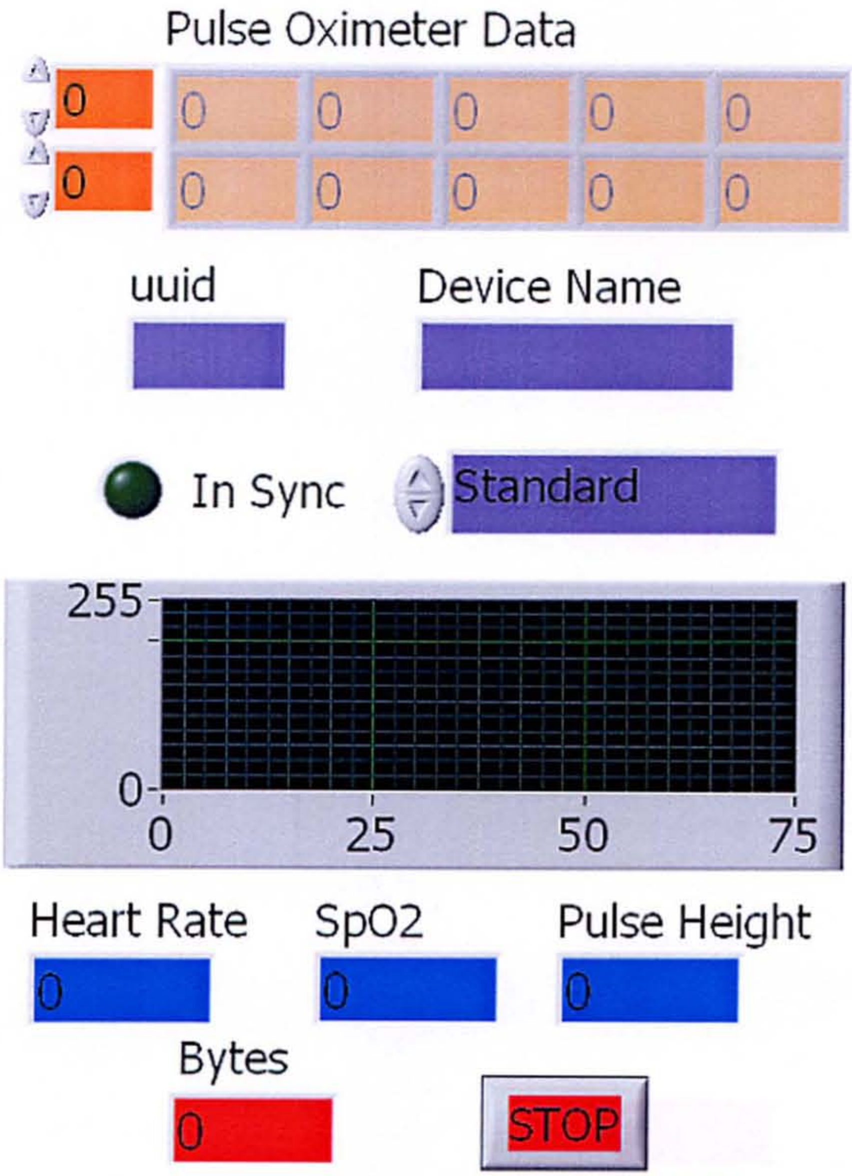


Figure 2.10 Front panel of Bluetooth Pulse Oximeter.

The front panel on the PDA looks like the one shown in the Figure 2.10. Block Diagram can be seen in Appendix C. The calculations for extracting the heart rate, SpO_2 and PPG waveform is the same as that done by the software of the Xpod. The only difference between the Bluetooth and the Xpod software is the configuration of the serial port. The blocks emulate the RS 232 configuration needed for the serial cable connection. The Bluetooth serial port is based on RFCOMM, which is different from a physical serial port. .

Bluetooth configuration software part includes the address of the Bluetooth device which needs to be detected by the PDA. It also includes the device name indicator to check if the correct Bluetooth device has been detected. A Universal Unique Identifier (UUID) is also specified for the Bluetooth pulse oximeter. This is in the Globally Unique Identifier (GUID) format which is a unique 128 bit number produced by the Windows OS or by some Windows applications to identify a particular component, application, file, database entry, and/or user.

2.2.6 Beat to Beat Interval Software

For post processing of the PPG signal a beat to beat interval program was developed. This program detects the peaks and then calculates the beat to beat interval. The program executes using the following steps:

1. It extracts the plethysmograph data from the saved file of the pulse oximeter data. Since the PPG data were located within the 3rd byte of the entire pulse oximeter data and index array was used to take the 3rd byte of data.

2. Peak detector block was used to detect the peak of the pulses in the PPG waveform.

3. To locate the peak the PPG waveform is scanned till the width of 60 as it gives accurate data with that number.

4. The locations of the peak are stored in an array and each location was subtracted from the previous one to determine the time interval between the beats or peaks.

5. The subtraction of all the array elements is again stored in a file and the data were then used to plot the beat to beat interval data.

The LabVIEW block diagram of the beat to beat interval can be seen in the Figure 2.11

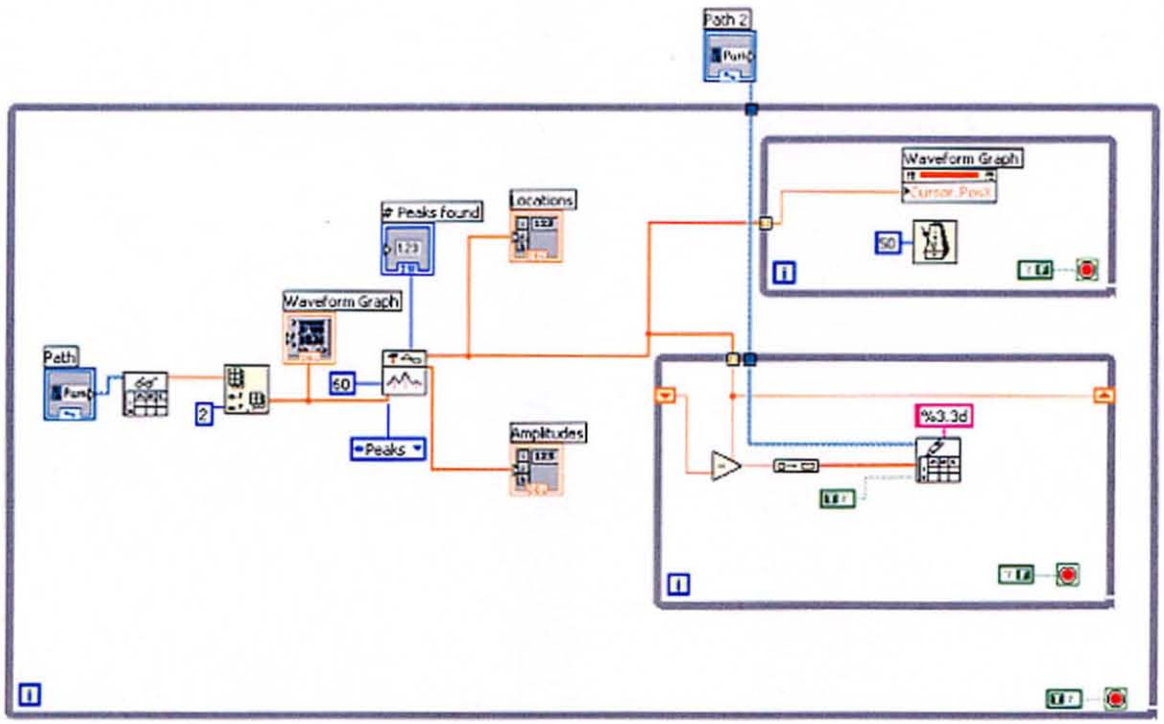


Figure 2.11 LabVIEW block diagram for calculating beat to beat interval.

CHAPTER 3

METHODS

3.1 Comparative Study of the Three Sensors

3.1.1 Comparative Study of the Sensors with Hand Movements

A person feeling cold tends to shiver and thus cause motion in the hand and fingers. It is important to use the correct sensor for an application like this to avoid incorrect readings from the pulse oximeter. The main aim of this test was to test which sensor would operate the best with the motion caused by the hand.

Five subjects were enrolled for this test. Each subject was to stand still for 30 seconds and then move his hand for the next 30 seconds. Data were collected for the whole one minute. This activity was performed with all the three sensors attached one at a time. The finger sensor was attached to the right index finger of the subjects. The ear sensor was attached to the right ear lobe and the reflectance sensor was attached to the forehead of each subject. Signal to noise ratio (SNR) was calculated of the PPG signal when used with each sensor. This was done using Microsoft Excel (Microsoft corporation, Seattle, USA). The formula used to calculate the SNR is shown below:

$$\text{SNR (dB)} = 20 \log 10 \; \frac{\text{Asignal RMS}}{\text{Anoise RMS}}$$

where A= Amplitude of the signal.

The greater the SNR better is the performance of the sensor with that particular motion. Thus, the SNR of the PPG signal with each sensor was compared and a preferred choice of sensor depending on the SNR for that particular movement was determined.

3.1.2 Comparative Study of the Sensors with Head Movements

This test was performed to compare the three sensors with head movements. Five subjects were enrolled for this study. Each subject was to stand still for the first 30 seconds and was then told to move his head vertically, to achieve vertical motion of the head for the next 30 seconds. Data were collected throughout one minute of the exercise.

The next test involved horizontal motion of the head and was performed in the same way as the vertical motion of the head. Data were collected for the entire one minute. The SNR was again calculated in the same way as mentioned above for both these tests. The sensor that produced least SNR value was preferred for activities including head movements.

3.1.3 Comparative Study of the Sensors with Body Movements

This test was performed to determine which sensor would work the best with entire body movement instead of solely hand or head movements in particular. The tests included twisting, walking and spot jogging. Each activity was conducted over 1 minute. During the first 30 seconds the person is still and the remaining the 30 seconds where the subject is doing each activity. All the three sensors were attached one at a time with each activity performed. SNR was calculated for each activity and for each sensor and depending on the ratio, the best sensor would be chosen for that particular activity. The greater the SNR, the better the sensor is in neglecting the motion. This would also help in determining which sensor should be used for monitoring the HR while a person is involved in body motion. Analysis of the HR data was done to determine which sensor could display the HR data during body motion and which sensor lost the signal due to motion. The time for which the sensor could display the HR data out of the total time was calculated to determine which sensor would work well. The sensor that the displayed the data for majority amount of time had better performance. SpO_2 analysis with motion was also done similar to that done for HR. A summary of all the various activities is given in the table below.

Table 3.1 Summary of Comparative Study of Sensors

<table>
<tr><th></th><th></th><th>Finger</th><th>Ear</th><th>Reflectance</th></tr>
<tr><td></td><td>Hand Movement</td><td rowspan="6">30 seconds of still data and 30 seconds of data with each activity</td><td rowspan="6">30 seconds of still data and 30 seconds of data with each activity</td><td rowspan="6">30 seconds of still data and 30 seconds of data with each activity</td></tr>
<tr><td rowspan="2">Head Motion</td><td>Vertical head movement</td></tr>
<tr><td>Horizontal head movement</td></tr>
<tr><td rowspan="3">Body Motion</td><td>Twisting</td></tr>
<tr><td>Walking</td></tr>
<tr><td>Spot jogging</td></tr>
</table>

3.2 Tests to Observe Changes in the PPG Waveform

Three subjects were enrolled in this study; no subject experienced known adverse event during or as a result of this study. Each subject was to perform the two tests to observe the changes in the PPG waveform. The tests included: Supine-Stand test, and Mental Activity.

3.2.1 Supine- Stand Test

The morphological analysis of the PPG from pulse oximeters provides an inexpensive tool to detect the baroreflex associated with standing in a diverse population of individuals. To simulate a rapid change in sympathetic tone resulting from a sudden decrease in arterial pressure, supine-stand test was performed. In this test, a person is in the supine position (lying down on his/her back) and then stands up suddenly. [13]

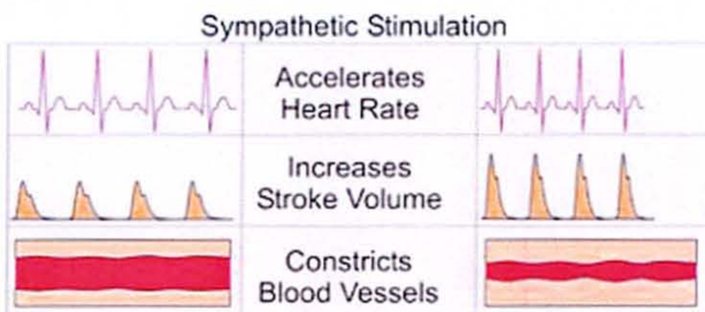


Figure 3.1 Changes with sympathetic stimulation [16].

Procedure for Supine- Stand Test:

1. Three subjects were to lie down on their back and this was to be done for 30 seconds.

2. After 30 seconds the subjects were told to stand up and stay in the standing position for the next one minute.

3. Data were collected for the entire 90 seconds and then analyzed.

4. For this particular test, the ear sensor was used. The finger and the reflectance sensor did not work well due to the motion of the standing position from the supine position. Because the ear lobe is less vasoactive site and is less susceptible to signal loss, it is a faster response site used and has greater accuracy when used with vasoconstriction and hypotension.

Hypothesis

This change in body position from horizontal to vertical causes a sudden drop in arterial pressure due to the effects of gravity pulling blood into the lower extremities. This activates the baroreceptor reflex associated with standing, sympathetic arterial constriction and increased heart rate.

The expected results would be an increase in the heart rate as soon as the person stands up and this can also be checked by using the beat to beat interval program. As the heart rate increases, the beat to beat interval should decrease.

3.2.2 Mental Activity

Active hyperemia is the increase in an organ blood flow that is associated with increased metabolic activity of an organ or tissue. Active hyperemia occurs during muscle contraction, increased mental activity, etc. Mental stress causes a substantial sympathetic response, thus increasing myocardial blood flow. At high levels of mental activity, the vasculature becomes maximally dilated thereby also resulting in maximal increase in the blood flow. [14]

Procedure for mental activity test

1. Three subjects were enrolled to perform this test.

2. Initially the subjects were told to relax to take their baseline data. This was done for one minute.

3. As soon as one minute passed, the person was asked to perform the mental task.

4. The mental task included solving a crossword puzzle. Some were also given word search puzzle.

5. They were to do the task for the next two minutes. Data were simultaneously collected as they performed the mental task. A total of three minutes of data were collected for this particular test.

6. For this particular test, the reflectance sensor was used as it accurately measures the blood flow of the brain. The finger sensor would not be a good choice as the person had to use his hands for performing the activity.

Hypothesis

By keeping the brain active and engaged it increases the vitality and builds reserves of brain cells and connections. During mental activity, the different parts of the brain have to do more work. Thus, the increase cognitive activity corresponds to increased blood flow.

The expected results would be an increase in the blood flow while the person is performing the mental task.

3.3 Data Collected from Bluetooth Pulse Oximeter

Data were also collected from the Bluetooth Pulse Oximeter to test the Bluetooth software. One minute of data were collected from the Bluetooth Pulse Oximeter. Heart Rate, plethysmograph and the SpO_2 was collected and then plotted using Microsoft Excel.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Results from the Comparative Study of the Three Sensors

4.1.1 Waveforms Obtained with Respect to Hand Movement

Waveforms obtained from subject 1 as an example is shown below in Figure 4.1. As mentioned in Table 3.1, still data was collected for 30 seconds and movement data was collected for the next 30 seconds, the whole experiment being of 60 seconds. PPG waveform of 10 seconds while the person is still and when the person performs the movement is plotted. The middle 10 seconds of still data out of the initial 30 seconds i.e., from 10 to 20 seconds is plotted on the left side. The right sides of the plot show the middle 10 seconds of the next 30 seconds of the movement data i.e., from 40 seconds to 50 seconds. The reason behind taking the middle 10 seconds of data was to avoid the initial adjustments made by the subject at the start of the experiment and to avoid the motion artifact at the 30th second caused with the start of the movement. This is true for all the other activities which include vertical and horizontal head movement, twisting, walking and spot jogging.

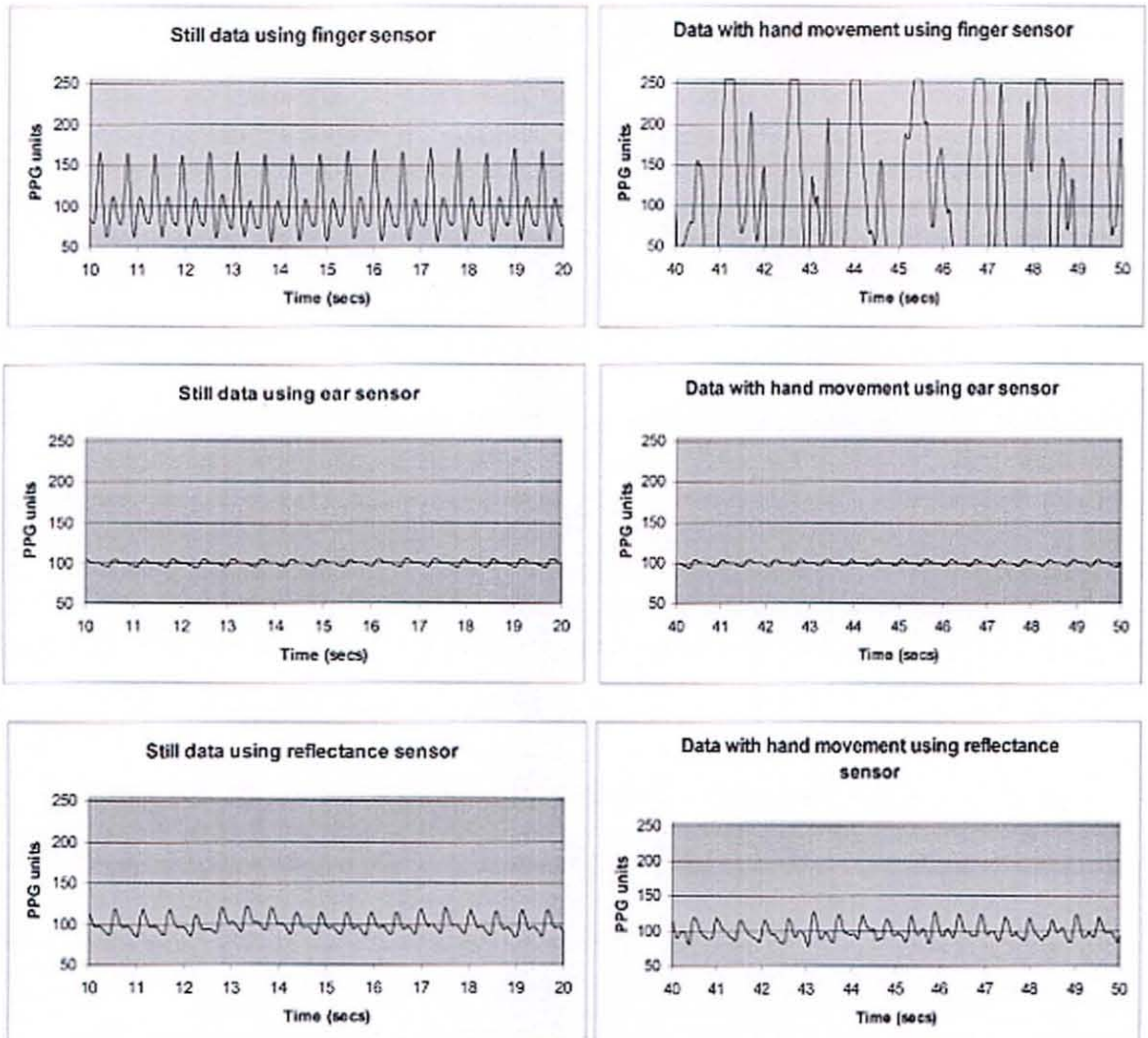


Figure 4.1 Waveforms obtained with hand movement using the three sensors.

From the above waveforms it can see that there is lots of noise while using the finger sensor (FS) during hand movement (1st plot to the right). The signal obtained from the ear sensor (ES) and the reflectance sensor (RS) with movements looks almost the same as the still data.

The SNR (dB) of the PPG waveform obtained using a finger sensor was -2.935 and that obtained using an ear and reflectance was 0.0038 and -0.0114, respectively as in case of subject 1. SNR (dB) for all the other five subjects was calculated with the finger, ear and reflectance sensor attached one at a time. The summary of all the five subjects is shown in the table below.

Table 4.1 Summary of SNR of the Five Subjects with Hand Movement

SNR (dB)				**Preferred choice of sensor in each subject**
Hand Movement	**Finger**	**Ear**	**Reflectance**	
Subject 1	-2.935	0.0038	-0.0114	Ear
Subject 2	-2.0663	-0.0036	0.0049	Reflectance
Subject 3	-0.2432	-0.0003	-0.0073	Ear
Subject 4	-0.1928	-0.0009	0.1456	Reflectance
Subject 5	-0.0259	-0.0059	0.0053	Reflectance
Average	**-1.09264**	**-0.00138**	**0.02742**	
Std. Deviation	**1.3240**	**0.0037**	**0.0665**	
Overall preferred choice with vertical head movement				**Reflectance/Ear**

The negative values of the SNR suggest that the sensor is affected with noise. The less the negative value or a positive value of SNR suggests that sensor would work well with the hand movement. So as seen in the Table 4.1 a reflectance sensor (RS) has the highest average SNR value of 0.02742 compared to -1.09264 and -0.00138, being that of the finger sensor (FS) and ear sensor (ES), respectively. Even when considering each of the subjects, it is seen that out of the five subjects, three subjects have the highest SNR with the reflectance sensor and two with ER.

By comparing the three sensors with hand movement, it can be seen that a finger sensor should be totally eliminated with activities involving hand movements as it has the lowest SNR and none of the subject show a good SNR when a FS is attached. An ES or a

RS could be preferred when a person wants to use Pulse Oximeter in activities involving hand movements like shivering etc. As seen from the Figure 4.1 (2nd plot), the ear sensor has very low signal amplitude and thus has a poor quality of PPG signal representation. By considering this aspect of the ear sensor it would be preferred to use a reflectance sensor which has better quality of signal representation.

4.1.2 Results with Respect to Head Movement

4.1.2.1 Vertical Head Movement

Waveforms obtained from the vertical head movements can be seen below.

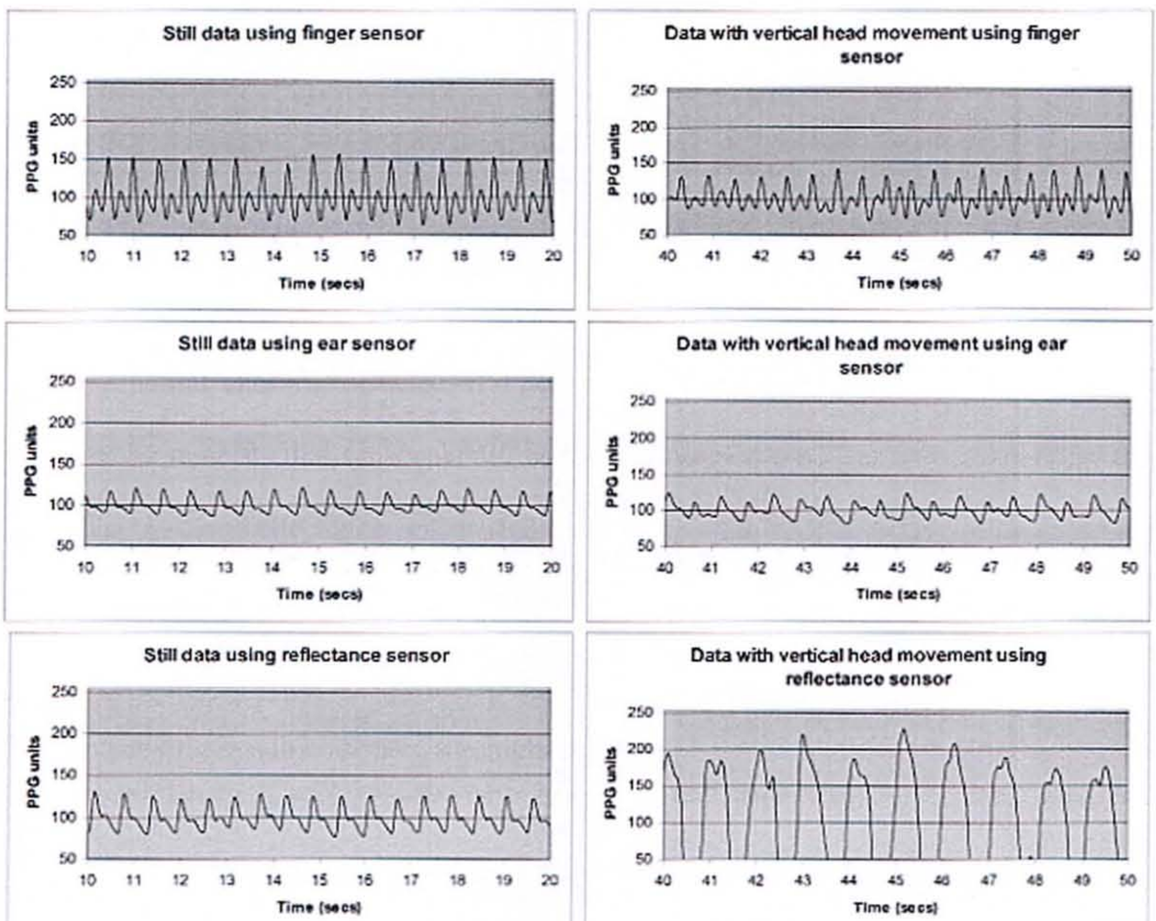


Figure 4.2 Waveforms obtained with vertical head movement using the three sensors.

Figures above show that the finger sensor and the ear sensor are not affected by the vertical head movement whereas with the reflectance sensor a lot of motion artifacts are seen with the vertical movement of the head.

The SNR calculated from the above graph using the FS was 0.035715, ES was 0.004573 and the RS was -2.15479 in case of subject 1. The summary of all the five subjects with the three sensors for this type of motion is listed in the table below.

Table 4.2 Summary of SNR of the Five Subjects with Vertical Head Movement

SNR (dB)				**Preferred choice of sensor in each subject**
Vertical Head Movement	**Finger**	**Ear**	**Reflectance**	
Subject 1	0.0357	0.0045	-2.1547	Finger
Subject 2	0.0346	-0.0045	-0.0497	Finger
Subject 3	-0.0376	0.0027	-2.0734	Ear
Subject 4	-0.1358	-0.0012	-0.0078	Ear
Subject 5	0.1591	-0.0013	-0.0327	Finger
Average	**0.0112**	**4E-05**	**-0.86366**	
Std. Deviation	**0.1084**	**0.0036**	**1.1419**	
Overall preferred choice with vertical head movement				**Finger/Ear**

From the above table for vertical head movements, the finger sensor has the highest average value of SNR compared to the other three. Even in this case considering each subject, three subjects give good SNR with finger and two subjects with ear, none of them show a good SNR with reflectance sensor.

Hence for applications involving head movements with a particular activity it is suggested that a RS should not be considered. It would be a better choice to go for a finger or an ear sensor. Comparing the Std. Deviations it is observed that they have higher value than the average and this is true as the number of subjects considered are less and each subject has lots of deviations from the average values and thus making the conclusions to be subjective too.

4.1.2.2 Horizontal Head Movement.

Waveforms obtained with horizontal head movements using the three sensors are shown below.

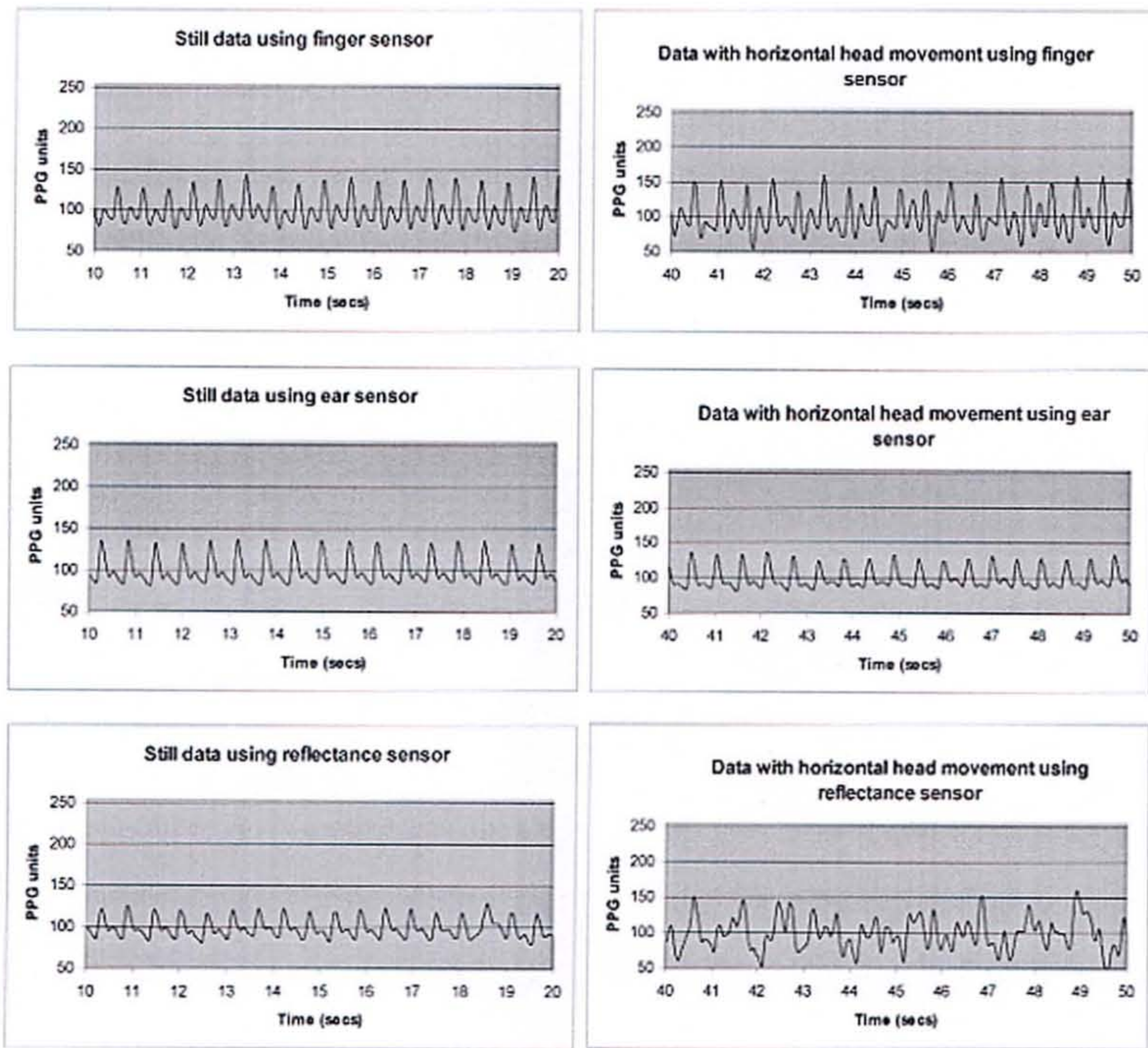


Figure 4.3 Waveforms obtained with vertical head movement using the three sensors.

As seen with the vertical head movement even the horizontal head movement gives out the same results. Reflectance sensor is very sensitive to horizontal head motion compared to ear and finger. The SNR for this particular subject with reflectance sensor (RS) was -0.15761, of ES was -0.00384 and with FS the SNR was -0.1124. Summary below includes the SNR of all the five subjects with this particular movement.

Table 4.3 Summary of SNR of the Five Subjects with Horizontal Head Movement

SNR (dB)				**Preferred choice of sensor in each subject**
Horizontal Head Movement	**Finger**	**Ear**	**Reflectance**	
Subject 1	-0.1124	-0.0038	-0.1576	Ear
Subject 2	0.0283	0.0027	-0.4056	Finger
Subject 3	-0.0043	0.0215	-0.0225	Ear
Subject 4	0.2614	0.0082	0.0041	Finger
Subject 5	0.0166	0.0008	-0.0169	Finger
Average	**0.0379**	**0.0059**	**-0.1197**	
Std. Deviation	**0.1368**	**0.0097**	**0.1722**	
Overall preferred choice with horizontal head movement				**Finger/Ear**

From the above analysis of the five subjects, it can be concluded that either a finger sensor or an ES could be preferred as a better choice for horizontal head movements. The reflectance sensor is again eliminated with this head movement as seen also with the vertical head movement. A RS tends to move with the movement of the head and the plot thus shows motion artifacts.

4.1.3 Body Movement

4.1.3.1 Twisting.

Waveforms obtained due to twisting are shown below.

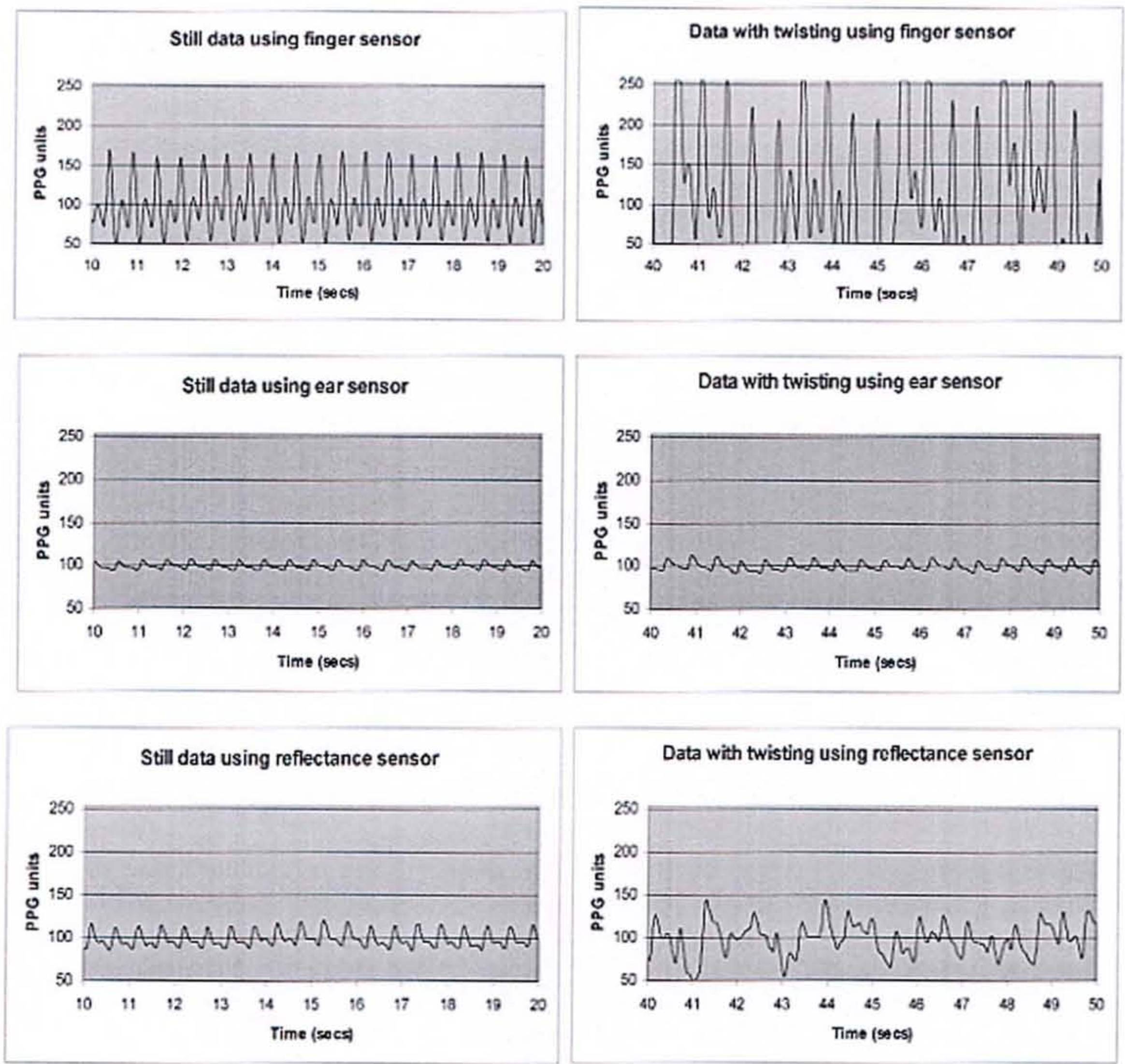


Figure 4.4 Waveforms obtained with twisting using the three sensors.

The SNR for this subject using a finger sensor was -1.94964, using an ear sensor was -0.00553 and that from a RS was -0.11084 with subject 1 as an example.

Table 4.4 Summary of SNR of the Five Subjects with Twisting

SNR (dB)				**Preferred choice of sensor in each subject**
Twisting	**Finger**	**Ear**	**Reflectance**	
Subject 1	-1.9496	-0.0055	-0.1108	Ear
Subject 2	-0.2824	-0.0042	-0.0145	Ear
Subject 3	-0.4851	-0.0272	-0.0230	Reflectance
Subject 4	-0.1352	0.0080	0.0055	Ear
Subject 5	-0.1671	-0.0020	-0.0227	Ear
Average	**-0.6039**	**-0.0062**	**-0.0331**	
Std. Deviation	**0.7647**	**0.0129**	**0.0450**	
Overall preferred choice with twisting				**Ear**

From Table 4.4, the average SNR of the ES is the highest as it has the least negative value compared to RS and FS. The above table also suggests that an ES works well for four subjects except in subject 3 which has higher SNR with reflectance sensor, though there seems to be not much difference in the SNR value of the ES and the RS with subject 3.

With twisting it can concluded that ES would be suggested as a good choice, as all the five subjects show the highest SNR when the ES is attached. Movements involving twisting should go for an ES compared to a RS and FS when using a Pulse Oximeter.

4.1.3.2 Walking.

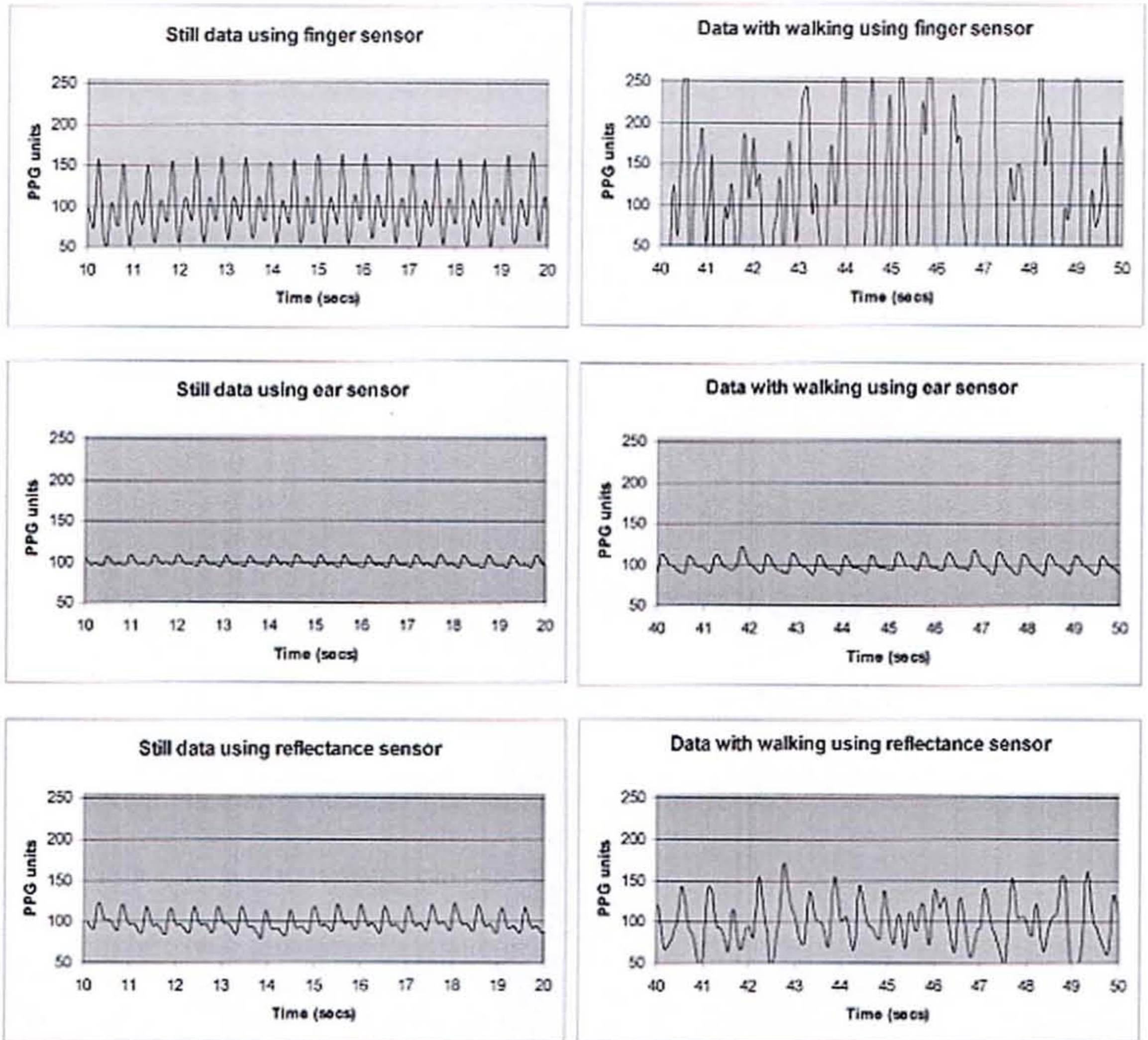


Figure 4.5 Waveforms obtained with walking using the three sensors.

From the graphs it can be seen that the ear sensor did not vary much with motion. So even for walking with respect to this subject the ear sensor was a good choice and gave least SNR. Table below gives the SNR of all the five subjects.

Table 4.5 Summary of SNR of the Five Subjects with Walking

SNR (dB)				**Preferred choice of sensor in each subject**
Walking	**Finger**	**Ear**	**Reflectance**	
Subject 1	-1.9213	-0.0235	-0.1834	Ear
Subject 2	-0.0236	0.0067	-0.0149	Ear
Subject 3	-0.2296	-0.0007	-0.0123	Ear
Subject 4	0.0336	0.0060	-0.0064	Finger
Subject 5	-0.1536	0.0013	-0.0122	Ear
Average	**-0.4589**	**-0.0020**	**-0.0458**	
Std. Deviation	**0.8241**	**0.0124**	**0.0770**	
Overall preferred choice with walking				**Ear**

Even in this case as the above case; the ES has least negative value of the average SNR. Comparing the three sensors, RS did not show a good SNR in any of the subjects with walking. Finger sensor seemed to show a higher SNR in subject 4 compared to ES. But with all the other subjects the ES again showed the highest SNR compared to the other two. Thus with walking it would be a good decision to go for an ES sensor rather than a FS or a RS.

4.1.3.3 Spot Jogging.

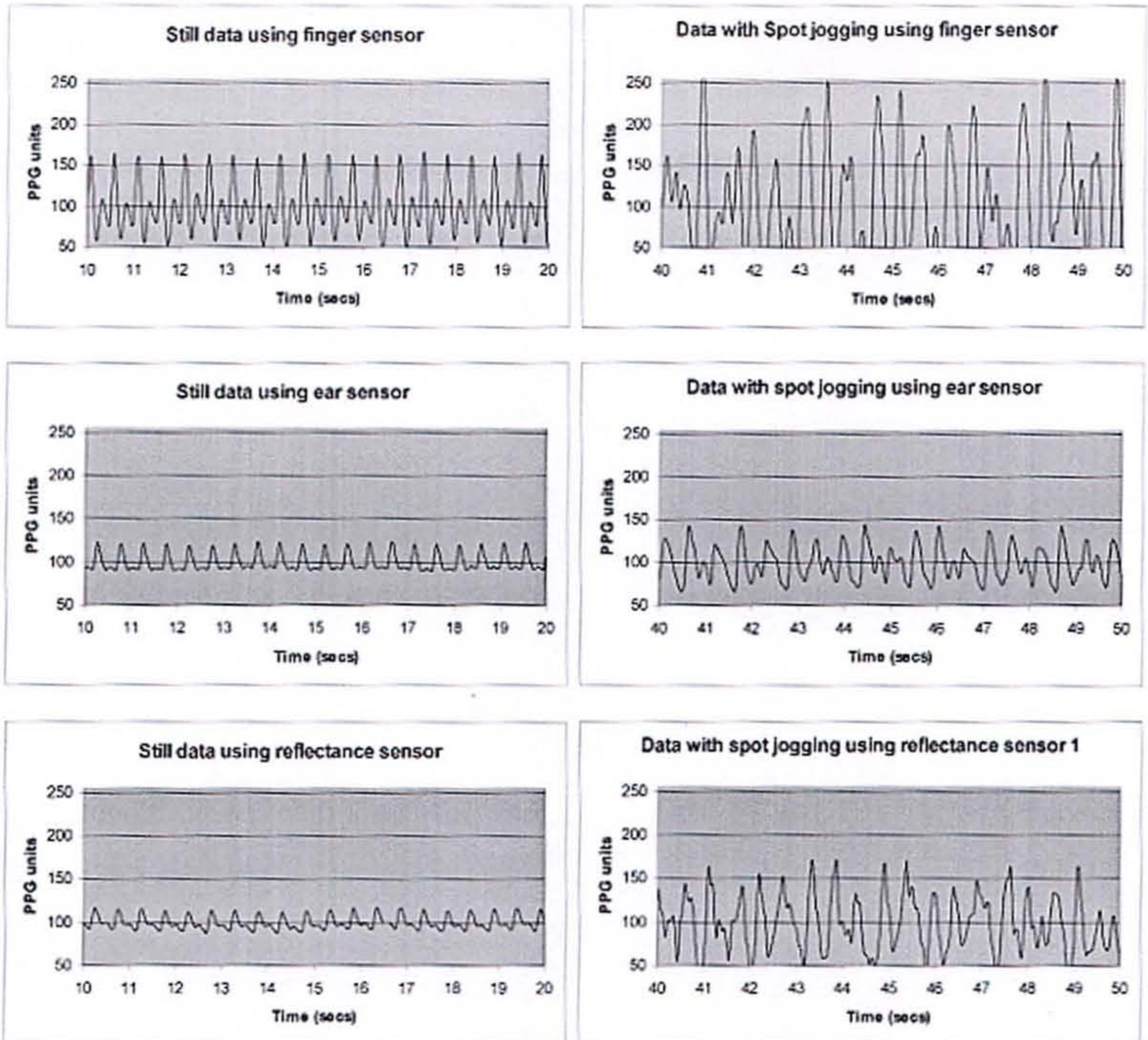


Figure 4.6 Waveforms obtained with spot jogging using the three sensors.

The table below shows the SNR obtained of the five subjects that were enrolled in spot jogging using all the three sensors.

Table 4.6 Summary of SNR of the Five Subjects with Spot Jogging

SNR (dB)				**Preferred choice of sensor in each subject**
Spot Jogging	**Finger**	**Ear**	**Reflectance**	
Subject 1	-1.8079	-0.1083	-0.2700	Ear
Subject 2	-0.1221	0.1770	-0.3379	Ear
Subject 3	-0.5330	-0.2772	-0.0607	Reflectance
Subject 4	-0.7288	-0.0014	-0.0180	Ear
Subject 5	-0.0055	0.0004	-0.0139	Ear
Average	**-0.6395**	**-0.0419**	**-0.1401**	
Std. Deviation	**0.7166**	**0.1667**	**0.1526**	
Overall preferred choice with spot jogging				**Ear**

It can be seen that the ES again has the highest SNR compared to the others and also shows that four subjects have higher SNR with ES. It is hence suggested that an ES would be a good choice with spot jogging activity. The average value of SNR with each activity is shown in the table below.

Table 4.7 Overall Average Value of SNR with Each Body Movement

Body Movement	**Average**			Overall Preferred Choice
	Finger	**Ear**	**Reflectance**	
Twisting	-0.6039	-0.0062	-0.0331	**Ear**
Walking	-0.4589	-0.002	-0.0458	**Ear**
Spot Jogging	-0.6395	-0.0419	-0.1401	**Ear**
Overall Average	**-0.5674**	**-0.0167**	**-0.073**	
Overall Std. Deviation	**0.0957**	**0.0219**	**0.0585**	

From the above table it can be concluded, that the ES has the highest SNR when considering all the three activities, thus making it an acceptable choice when compared to the other two sensors for activities involving all the three body movements.

4.1.4 Heart Rate Monitoring with Motion

Along with motion another concern would be monitoring of heart rate, as to if there was a continuous value of HR outputted by the sensor or did the sensor lose the signal with motion. The amount of good signal obtained along with motion artifact caused by twisting of the body, walking and spot jogging would be a parameter to compare the sensor. An empirical study was performed to monitor heart rate with and without motion artifacts.

The HR plots of the five subjects i.e., while twisting, walking and spot jogging along with each sensor attached at a time are shown below. Each plot consists of the comparison of the HR value with the three sensors along with each activity. Each sensor was attached to the subject at a time and not simultaneously for a period of one minute.

4.1.4.1 Twisting.

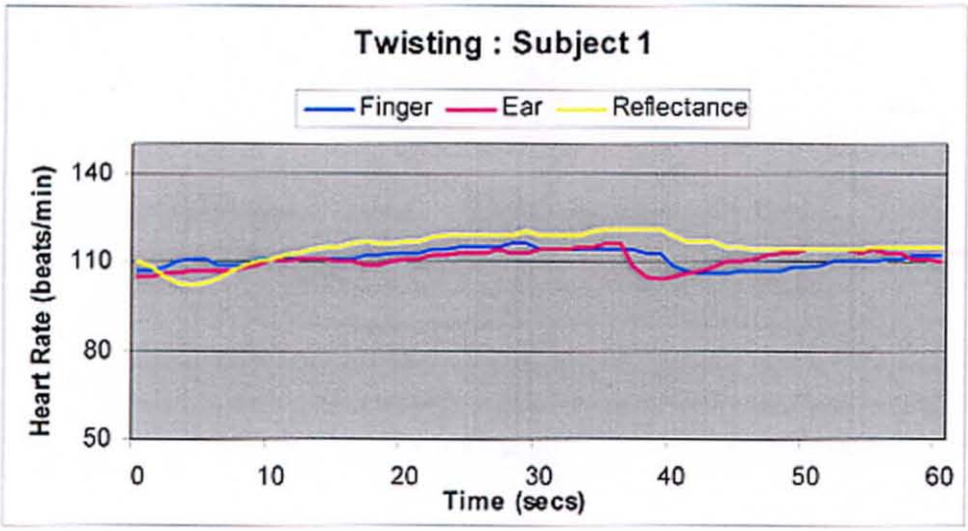


Figure 4.7 Heart Rate measured from the three sensors with twisting in subject 1.

As seen from the above plot each sensor showed a good HR plot along with the twisting motion. None of the sensors lost the signal due to motion. Thus there was a signal obtained for 100% of the total time from all the three sensors.

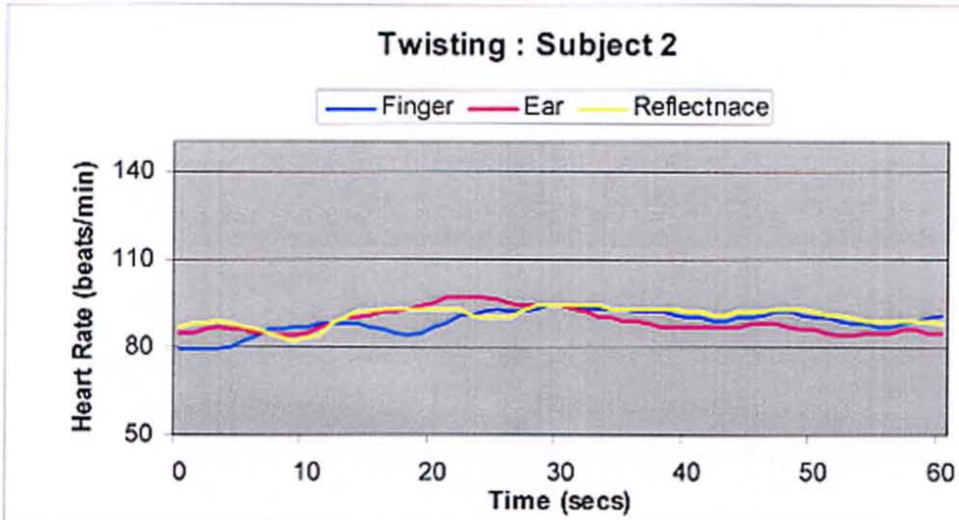


Figure 4.8 Heart Rate measured from the three sensors with twisting in subject 2.

Heart rate monitoring in subject 2 was also smooth with all the three sensors and signal was obtained for 100% of the total time from all the three sensors.

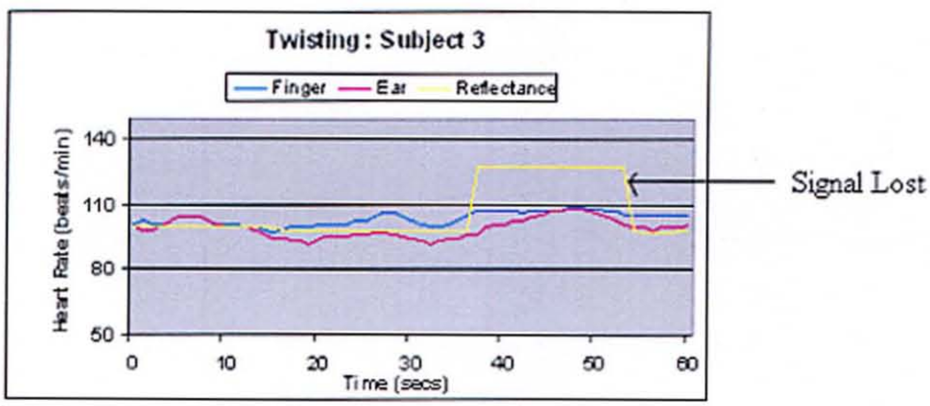


Figure 4.9 Heart Rate measured from the three sensors with twisting in subject 3.

This plot is not in agreement with the above two subjects. In subject 3 it can be seen that the RS showed some reading of the HR for only 71.67% of the total time, rest of the time just showed a constant value of HR as the sensor lost the signal due to motion. It was assumed that may be due to the motion the sensor must have shifted and thus lost the signal for a certain period of time. The FS and the ES unlike the RS showed some reading of the HR for 100% of the total time.

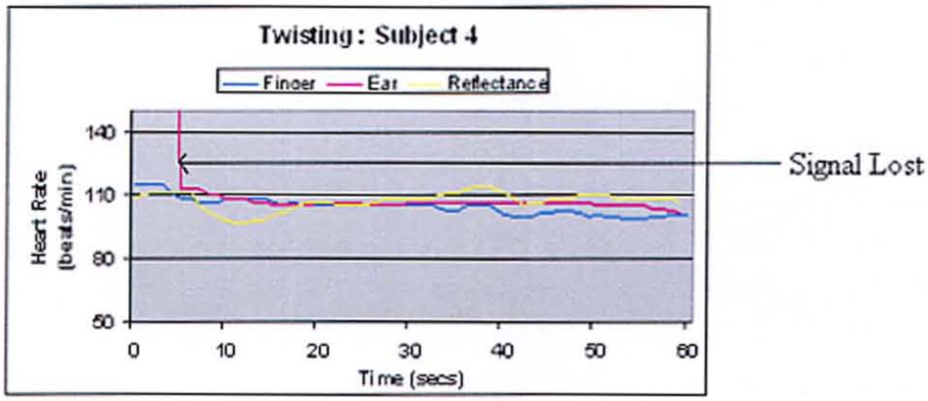


Figure 4.10 Heart Rate measured from the three sensors with twisting in subject 4.

In subject 4 it was observed that the ear sensor showed readings of HR for 91.6% of the total time of the experiment and this change was in the initial plot and not after 30 seconds where in the person starts twisting. It was assumed that this was due to low perfusion at the ear site of this particular subject which restrained the ES to acquire signal from the artery of the ear as soon as the ES was attached.

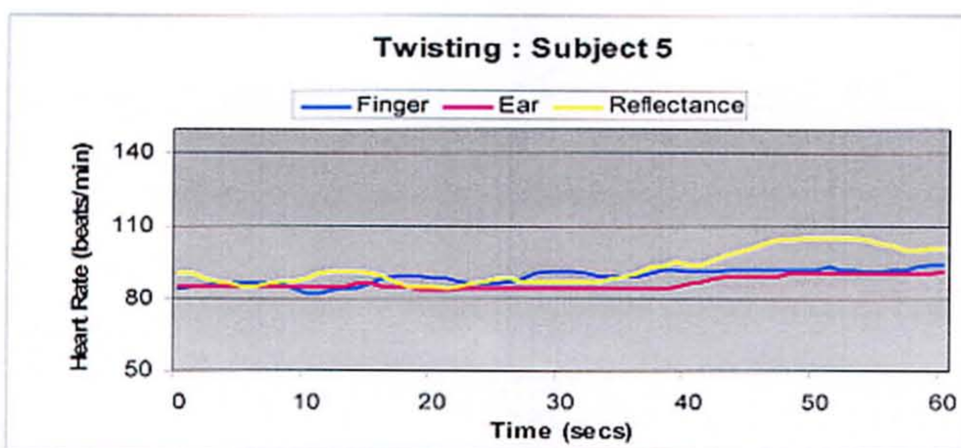


Figure 4.11 Heart Rate measured from the three sensors with twisting in subject 5.

With subject 5 all the three sensors showed a HR value for 100 % of the total time of the experiment. Summary of all the five subjects is shown below.

Table 4.8 Total Time for which HR Data was Observed with Twisting from each Sensor

Total time for which HR value was observed			
Twisting	**Finger**	**Ear**	**Reflectance**
Subject 1	100%	100%	100%
Subject 2	100%	100%	100%
Subject 3	100%	100%	71.67%
Subject 4	100%	91.6% (but not due to motion)	100%
Subject 5	100%	100%	100%
Average	**100.00%**	**98.32%**	**94.33%**
Std. Deviation	**0.00%**	**3.75%**	**12.67%**

* this was due to low perfusion of the ear sensor for a certain period of time.

The finger sensor provided a HR value for all the subjects, where as the ES provided a HR value for four subjects but for subject 4 it could provide a signal only for 91.6% of the time. RS sensor provided the HR value for subject 3 only for 71.67% of time. Thus, for twisting a FS could be used for monitoring HR with motion.

Also, from the above plots it can be seen that the acquisition of the signals along with motion is also subjective. It depends on the subject's perfusion level at the particular sensor site. It is also seen in Figure 4.1 (2^{nd} plot) that the ES has very low amplitude and thus a poor quality of signal. Hence it is very liking for the Ear sensor to loose signal due to perfusion in some subjects during any kind of motion.

4.1.4.2 Walking.

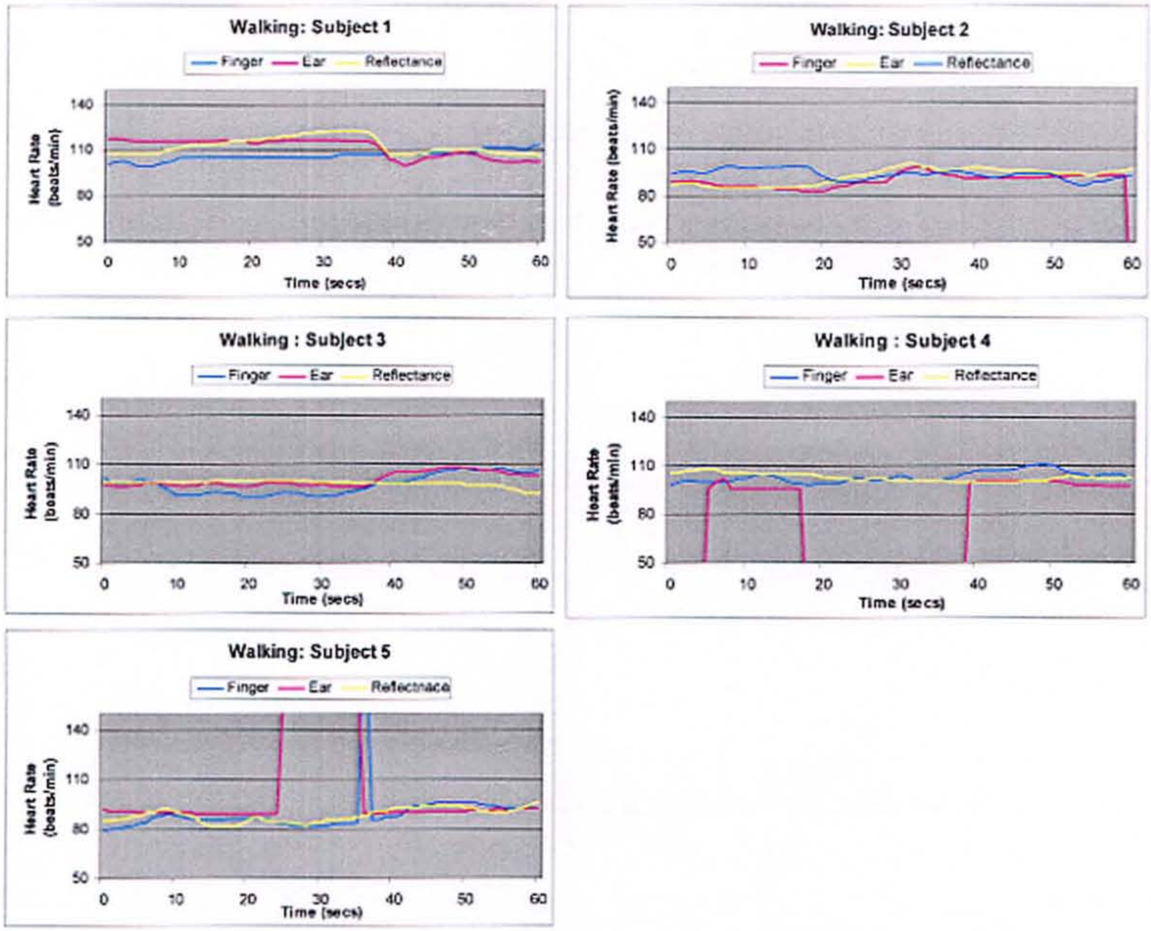


Figure 4.12 Heart Rate measured from the three sensors with walking.

Table 4.9 Total Time for which HR data was Observed with Walking from each Sensor

Total time for which HR value was observed			
Walking	**Finger**	**Ear**	**Reflectance**
Subject 1	100%	100%	100%
Subject 2	98.33%	100%	100%
Subject 3	100%	100%	100%
Subject 4	100%	56.67%	100%
Subject 5	98.33%	81.67%	100%
Average	**99.33%**	**87.67%**	**100.00%**
Std. Deviation	**0.91%**	**19.06%**	**0.00%**

From Table 4.9 it can be seen that, the finger sensor lost the signal in case of two subjects, but not for a long period of the time, thus giving an average of 99% of good signal. While in subject 4 and 5, the total time for which the ES could provide a HR value was for 56.67% and 81.67%, respectively. In case of subject 4 it was seen that it could give out a HR value only for half of the total time of the experiment and the reason being the same as that observed in the twisting experiment. Thus with more motion the ES tends to loose more signal due to low perfusion. The same reason was true for subject 5. Comparing the three sensors, RS showed signal for 100% of the total time in all the subjects. Therefore, for walking a RS could be a good choice while monitoring HR with motion.

4.1.4.3 Spot Jogging.

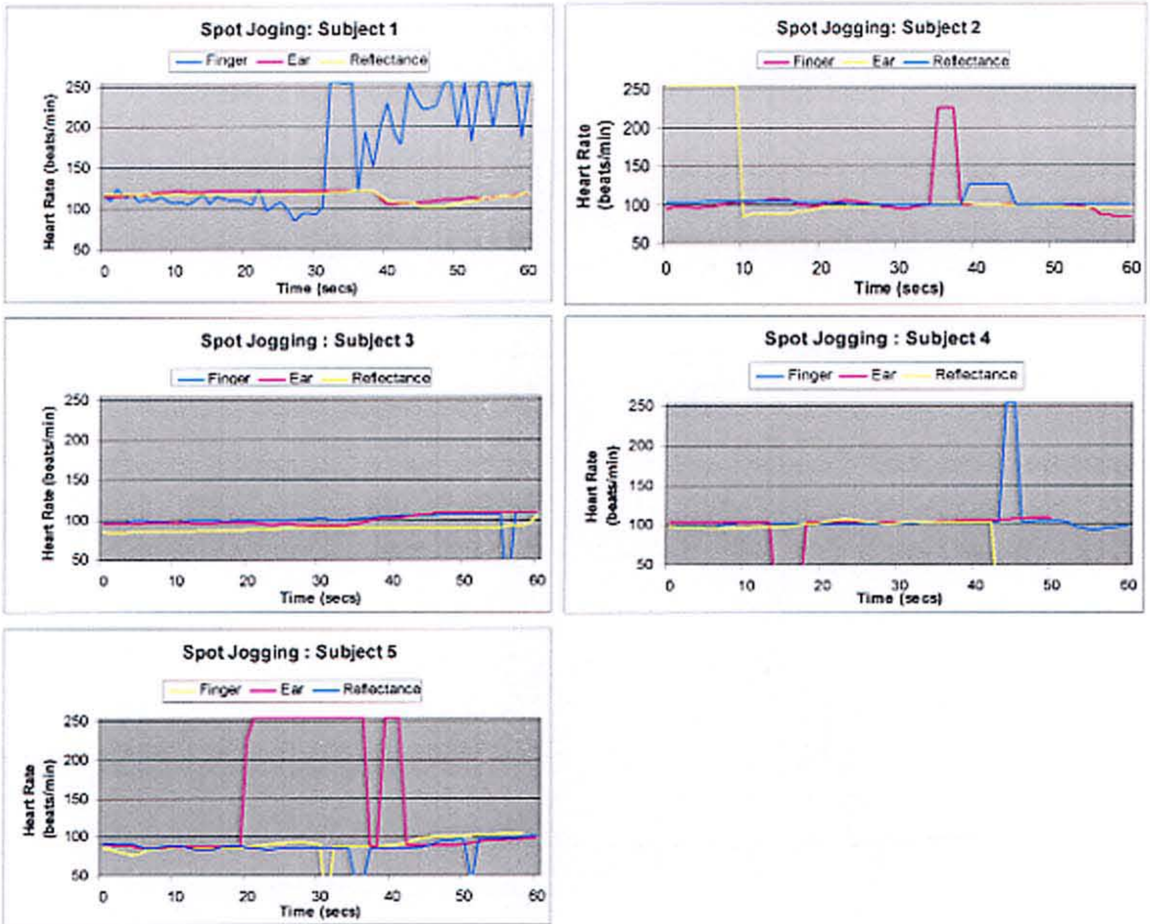


Figure 4.13 Heart Rate measured from the three sensors with spot jogging.

Table 4.10 Total Time for which HR data was Observed with Spot Jogging from each Sensor

Total time for which HR value was observed			
Spot jogging	**Finger**	**Ear**	**Reflectance**
Subject 1	55%	100%	100%
Subject 2	95%	83.33%	90%
Subject 3	98%	100%	100%
Subject 4	96.67%	93.33% (but not due to motion)	73.33%
Subject 5	98%	66.66%	95%
Average	**88.67%**	**88.66%**	**91.67%**
Std. Deviation	**18.87%**	**14.06%**	**11.06%**

* this was due to low perfusion of the ear sensor for a certain period of time.

From the table above, by considering the average values of the total time the HR value was obtained from all the three sensors. RS seems to having the highest average value for which the signal was available. FS and the ES have the same average value.

Table 4.11 Average Value of HR Analysis with Motion for each Body Movement

Total time for which HR value was observed			
	Finger	**Ear**	**Reflectance**
Twisting	100.00%	98.32%	94.33%
Walking	99.33%	87.67%	100%
Spot jogging	88.67%	88.66%	91.67%
Average	**96.00%**	**91.55%**	**95.33%**
Std. Deviation	**6.36%**	**5.88%**	**4.25%**

Considering all the three movements together for HR monitoring with motion the finger sensor has the higher percentage for which it could provide the HR value. It showed the HR value for 96% of the total time. Average value of FS is also comparable to the average value of RS. Thus either one can be used for monitoring the HR with motion, eliminating the ES for this application.

The overall analysis of HR monitoring with motion would include the three parameters such as the SNR of each sensor, the average percentage value of each sensor for the time they could give out a HR value and the total number of subjects out of 15, in which they could provide 100% of signal. The summary is shown in the table below.

Table 4.12 Summary of the HR Analysis

HR analysis with motion	**Finger**	**Ear**	**Reflectance**	Preferred choice
SNR	-0.5674	-0.0167	-0.073	**Ear**
Number of subjects in which sensor could provide 100% of signal	8	9	11	**Reflectance**
Average Percentile value for the time they could provide HR data	96%	91.55%	95.33%	**Finger/ Reflectance**

It is seen that all the three sensors worked better with either one of the conditions. Thus it was difficult to conclude on any one. But as from the table it can be seen that on an average a RS could be used for monitoring the HR with motion as two of the parameters are in favor of the RS sensor, though a firm conclusion cannot be made from this experiment. Even a finger sensor can be used as it gives the HR data for 96% of the total time and an ES when considering SNR parameter.

4.1.5 SpO₂ Analysis

4.1.5.1 Twisting.

Results from five subjects with twisting are shown below.

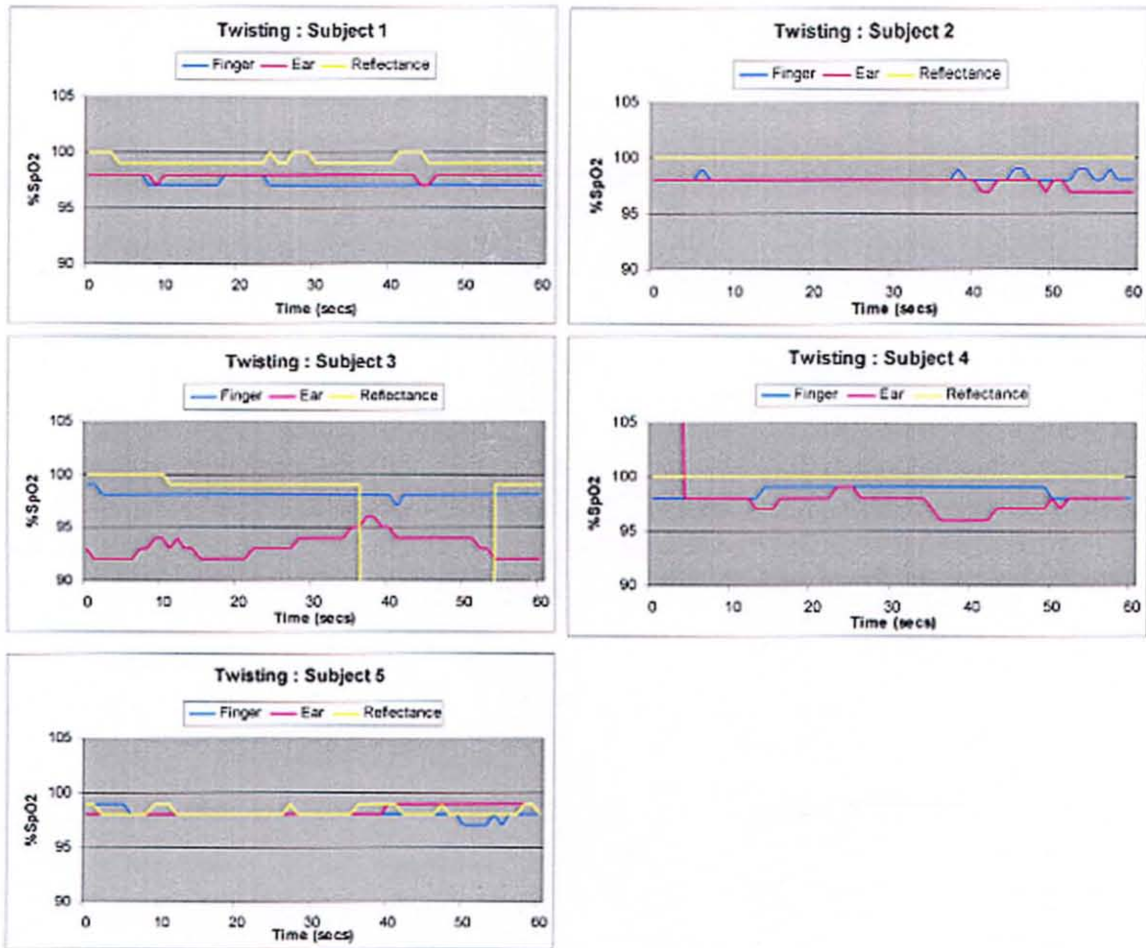


Figure 4.14 SpO_2 monitoring with twisting using the three sensors.

4.1.5.2 Walking.

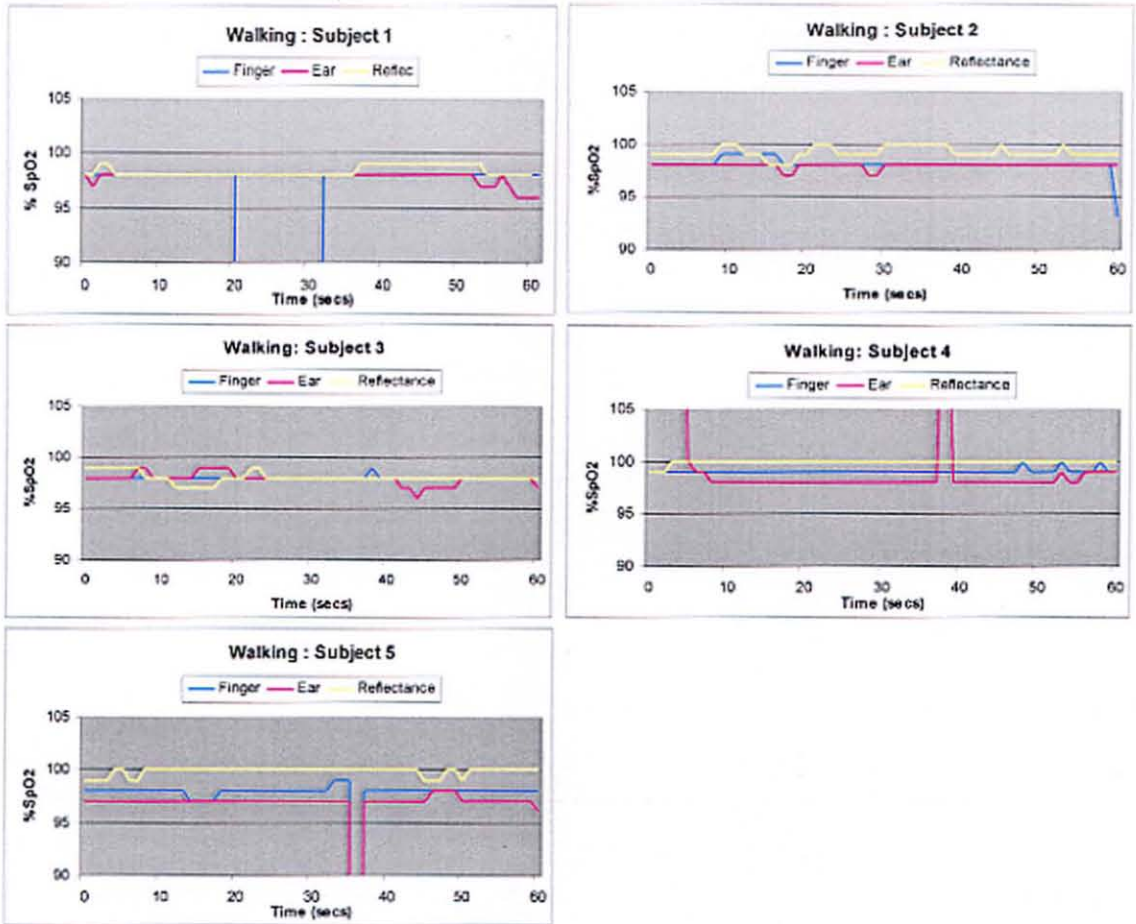


Figure 4.15 SpO_2 monitoring with walking using the three sensors.

4.1.5.3 Spot Jogging.

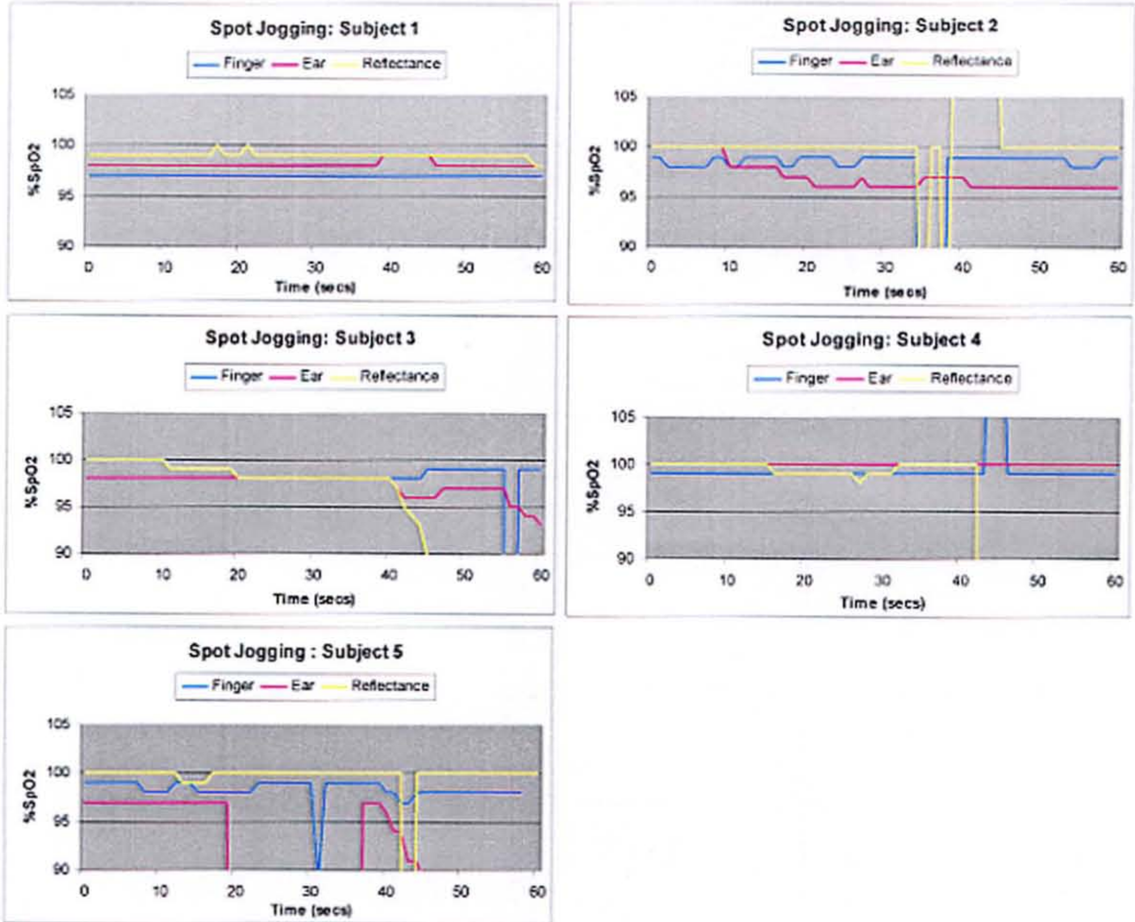


Figure 4.16 SpO_2 monitoring with spot jogging using the three sensors.

The tables below give the summarize view about the percent of signal lost by each of the sensor with each activity.

Table 4.13 Total Time for which SpO_2 Data was Observed with Twisting from each Sensor

Total time for which SpO_2 data was observed			
Twisting	**Finger**	**Ear**	**Reflectance**
Subject 1	100%	100%	100%
Subject 2	100%	100%	100%
Subject 3	100%	100%	71.66%
Subject 4	100%	93.33% (not due to motion)	100%
Subject 5	100%	100%	100%
Average	**100.00%**	**98.66%**	**94.33%**
Std. Deviation	**0.00%**	**2.98%**	**12.67%**

Table 4.14 Total Time for which SpO_2 Data was Observed with Walking from each Sensor

Total time for which SpO_2 data was observed			
Walking	**Finger**	**Ear**	**Reflectance**
Subject 1	81.66%	100%	100%
Subject 2	100%	100%	100%
Subject 3	100%	100%	100%
Subject 4	100%	90.00%	100%
Subject 5	100%	98.33%	100%
Average	**96.33%**	**97.67%**	**100.00%**
Std. Deviation	**8.20%**	**4.35%**	**0.00%**

Table 4.15 Total Time for which SpO2 Data was Observed with Spot Jogging from each Sensor

Total time for which SpO_2 data was observed			
Spot jogging	**Finger**	**Ear**	**Reflectance**
Subject 1	100%	100%	100%
Subject 2	95%	100%	86.66%
Subject 3	98.33%	100%	100%
Subject 4	96.66%	100%	65%
Subject 5	100%	71.67%	98.33%
Average	**98.00%**	**94.33%**	**90.00%**
Std. Deviation	**2.17%**	**12.67%**	**15.05%**

The overall summary of the SpO_2 analysis can be seen in the table below.

Table 4.16 Average Value of SpO_2 Analysis with Motion for each Body Movement

Total time for which SpO_2 data was observed			
	Finger	**Ear**	**Reflectance**
Twisting	100.00%	98.66%	94.33%
Walking	96.33%	97.67%	100%
Spot jogging	98.00%	94.33%	90.00%
Average	**98.11%**	**96.89%**	**94.78%**
Std. Deviation	**1.84%**	**2.27%**	**5.01%**

Now depending on the three parameters as shown with the HR monitoring experiment, table below gives the results for SpO_2 monitoring experiment.

Table 4.17 Summary of SpO_2 Analysis

SpO_2 analysis with motion	**Finger**	**Ear**	**Reflectance**	Preferred choice
SNR	-0.5674	-0.0167	-0.073	**Ear**
Number of subjects in which sensor could provide 100% of signal	11	11	11	**Ear/Reflectance/ Finger**
Average Percentile value for the time they could provide SpO_2 data	98.11%	96.89%	94.78%	**Finger**

Based on similar analysis as done for HR monitoring experiment, SpO2 monitoring experiment shows that a finger sensor seems to work well for SpO_2 monitoring. This can be concluded as two of the parameters are in favor with the finger sensor.

The overall analysis of the comparative study of the sensors with different movements/activities can be shown below.

Table 4.18 Results from the Comparative Study of the Three Sensors

<table>
<tr><th colspan="2">Activities / Movements</th><th>Preferred choice of sensor(s)</th><th>Sensor(s) to be eliminated</th><th>Overall Preferred Choice</th></tr>
<tr><td>Hand Movement</td><td></td><td>Ear/ Reflectance</td><td>Finger</td><td>Ear/ Reflectance</td></tr>
<tr><td rowspan="2">Head Movements</td><td>Vertical Head Movement</td><td>Finger/ Ear</td><td>Reflectance</td><td rowspan="2">Finger/Ear</td></tr>
<tr><td>Horizontal Head Movement</td><td>Finger/ Ear</td><td>Reflectance</td></tr>
<tr><td rowspan="3">Body Movements</td><td>Twisting</td><td>Ear</td><td>Finger/Reflectance</td><td rowspan="3">Ear</td></tr>
<tr><td>Walking</td><td>Ear</td><td>Finger/Reflectance</td></tr>
<tr><td>Spot Jogging</td><td>Ear</td><td>Finger/Reflectance</td></tr>
<tr><td rowspan="3">HR monitoring with motion</td><td>Twisting</td><td>Finger</td><td>Ear/ Reflectance</td><td rowspan="3">Reflectance</td></tr>
<tr><td>Walking</td><td>Reflectance</td><td>Ear/ Finger</td></tr>
<tr><td>Spot Jogging</td><td>Reflectance</td><td>Ear/ Finger</td></tr>
<tr><td rowspan="3">SpO_2 monitoring with motion</td><td>Twisting</td><td>Finger</td><td>Ear/ Reflectance</td><td rowspan="3">Finger</td></tr>
<tr><td>Walking</td><td>Reflectance</td><td>Ear/ Finger</td></tr>
<tr><td>Spot Jogging</td><td>Finger</td><td>Ear/ Reflectance</td></tr>
</table>

4.1.6 Results from Mental Activity

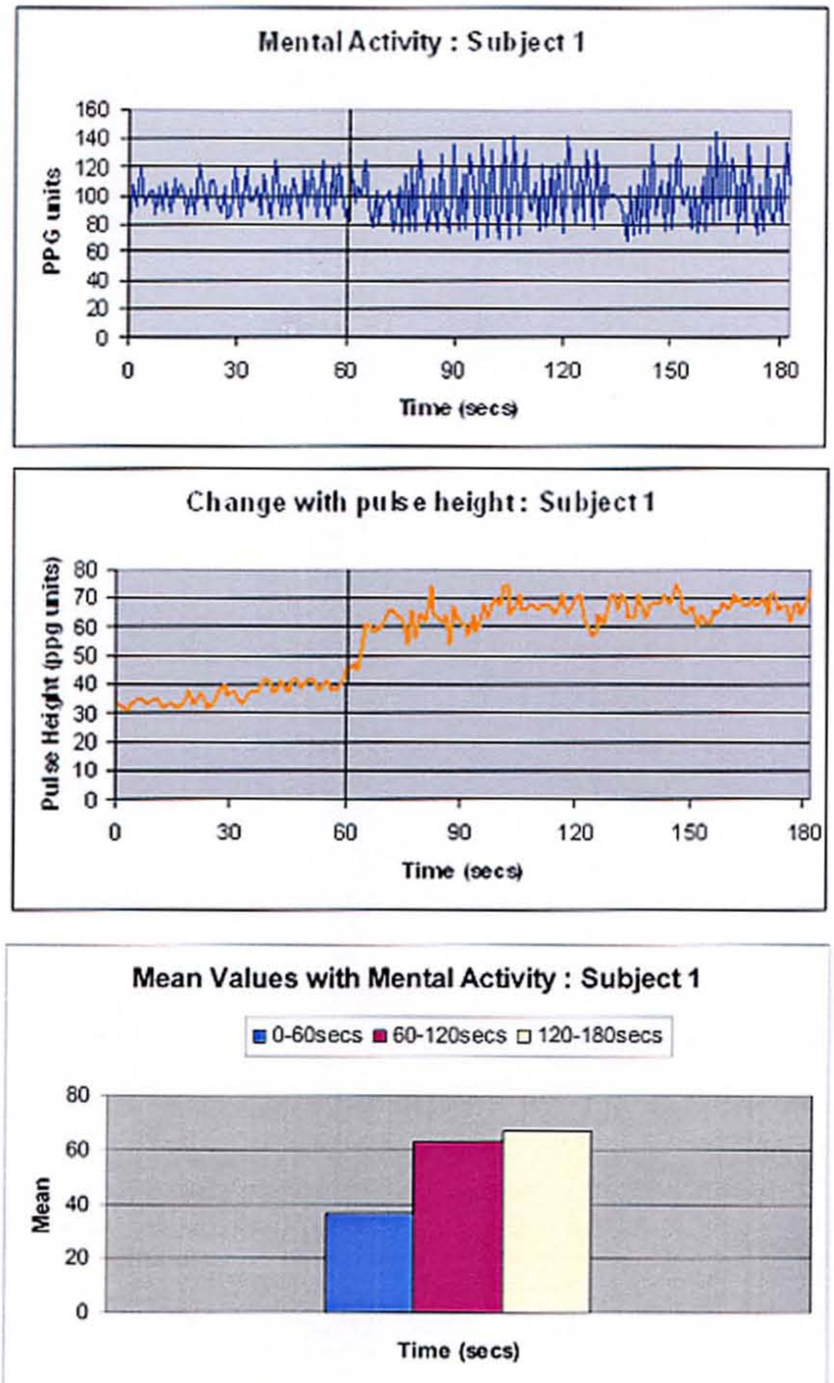


Figure 4.17 Subject 1: PPG waveform (1st plot), pulse height waveform (2nd plot) and mean values of each 60 secs of data (3rd plot).

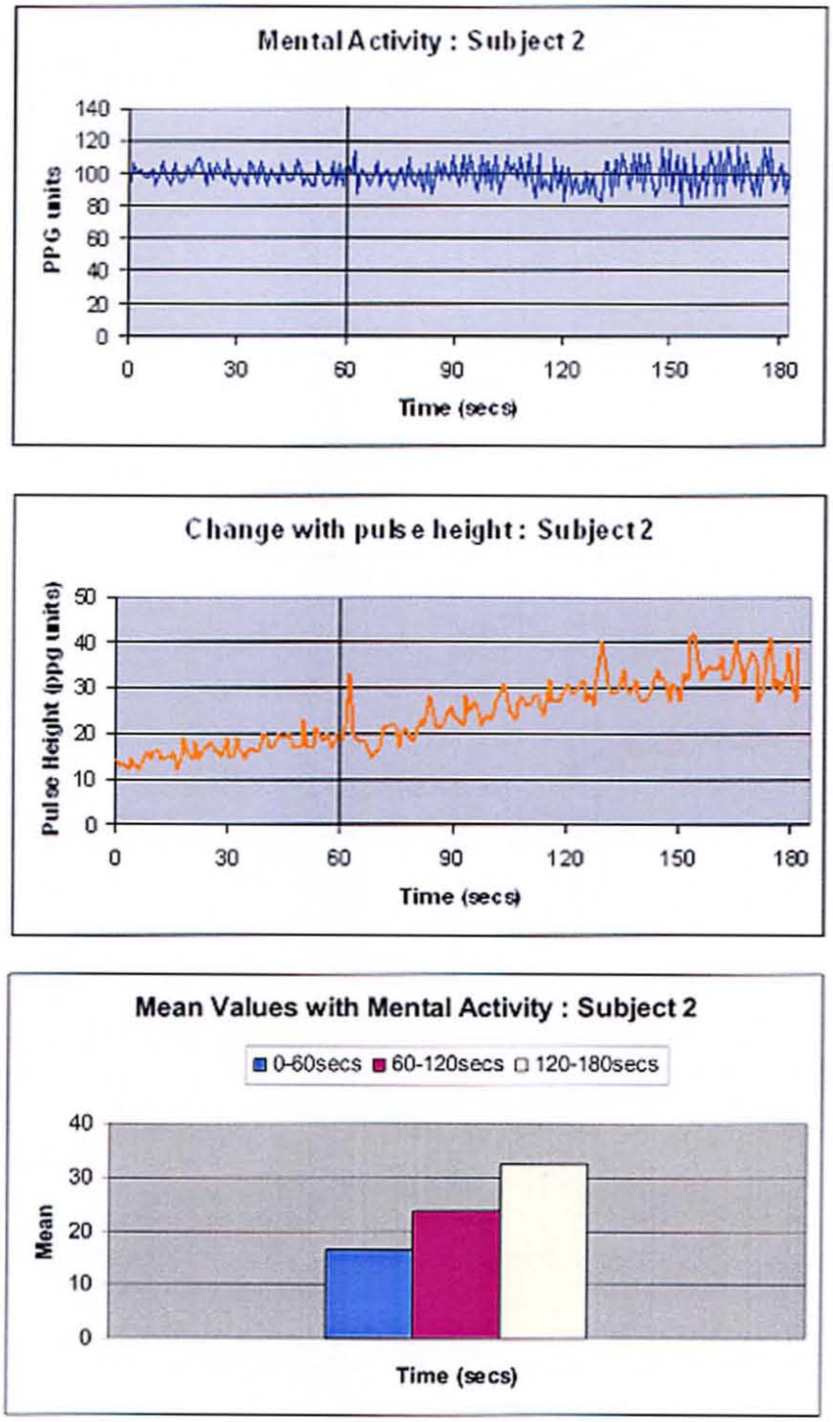


Figure 4.18 Subject 2: PPG waveform (1st plot), pulse height waveform (2nd plot) and mean values of each 60 secs of data (3rd plot).

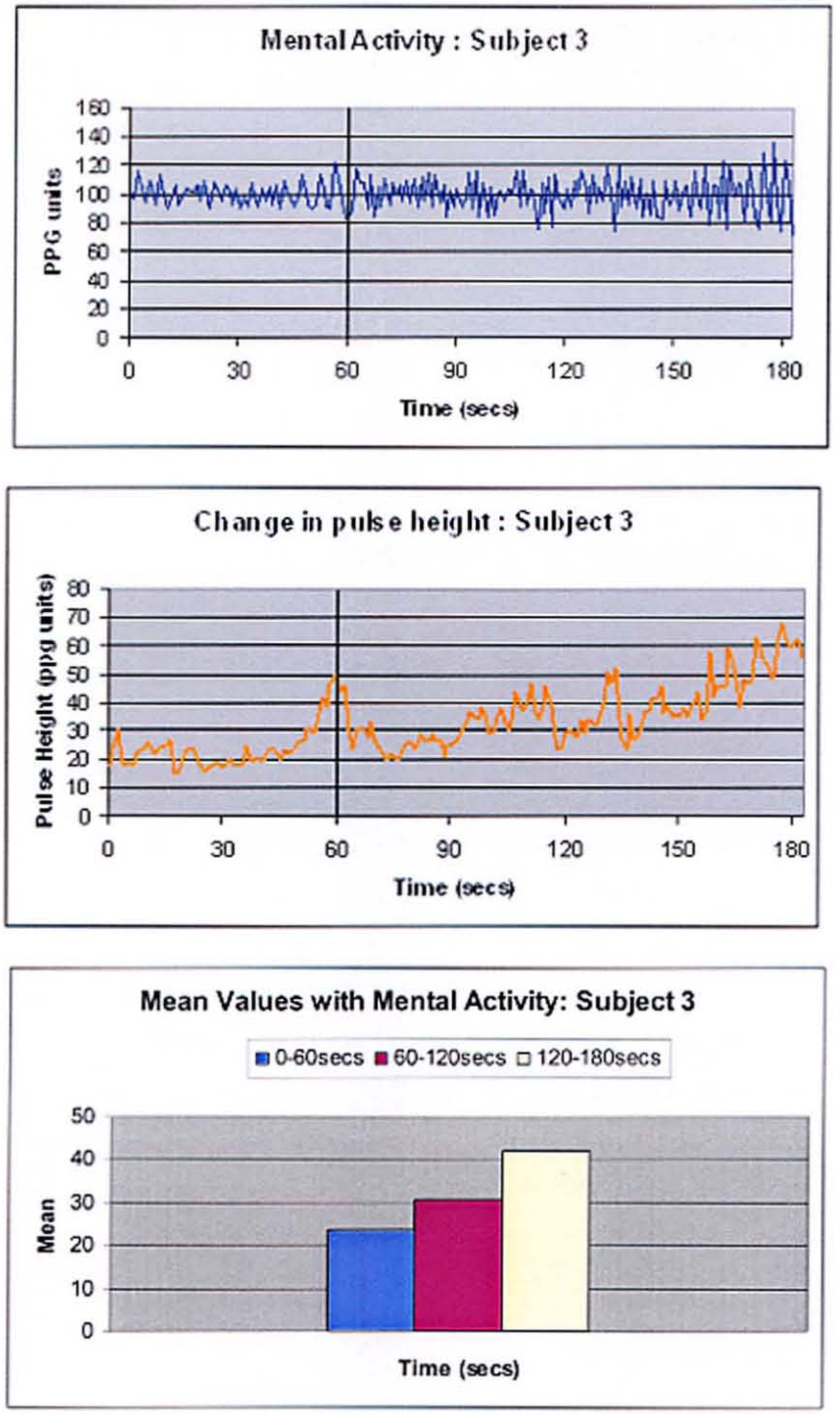


Figure 4.19 Subject 3: PPG waveform (1st plot), pulse height waveform (2nd plot) and mean values of each 60 secs of data (3rd plot).

Table 4.19 Overall Summary of Mental Activity

	Average Value with Mental Activity (ppg units)		
Mental Activity	**Subject 1**	**Subject 2**	**Subject 3**
0-60 secs	36.45	16.5167	23.45
60-120 secs	63.05	23.6	30.8833
120-180 secs	66.7667	32.3833	41.9833

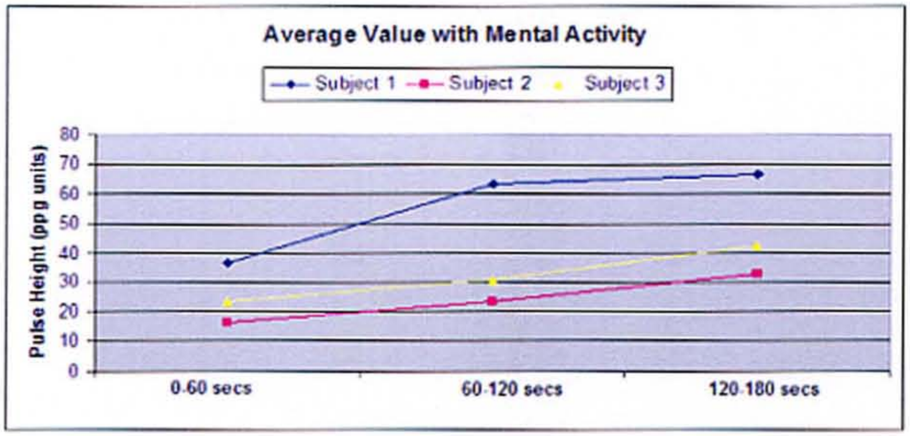


Figure 4.20 Average value of the pulse height with mental activity of the three subjects.

From the plots above it is seen that there is an increase in the pulse height of the PPG waveform once the person is given the task to perform, after 60 seconds. Thus with the introduction of the mental activity each subject show an increase in the pulse height after 60 seconds indicating an increase in the blood flow with the mental stress. From the mean graphs and Table 4.20, average of each 60 seconds of data shows an increase in the value. Thus it can be concluded that mental task does have an affect on the overall blood flow of the body and makes the brain more active. Therefore mental task increases the blood flow of the body and under mental stress the vasculature dilates and there is a sympathetic response which leads to increase in myocardial blood flow.

4.1.7 Supine Stand Test

The line at the 30th second indicates a change from supine position to stand position performed by the subject.

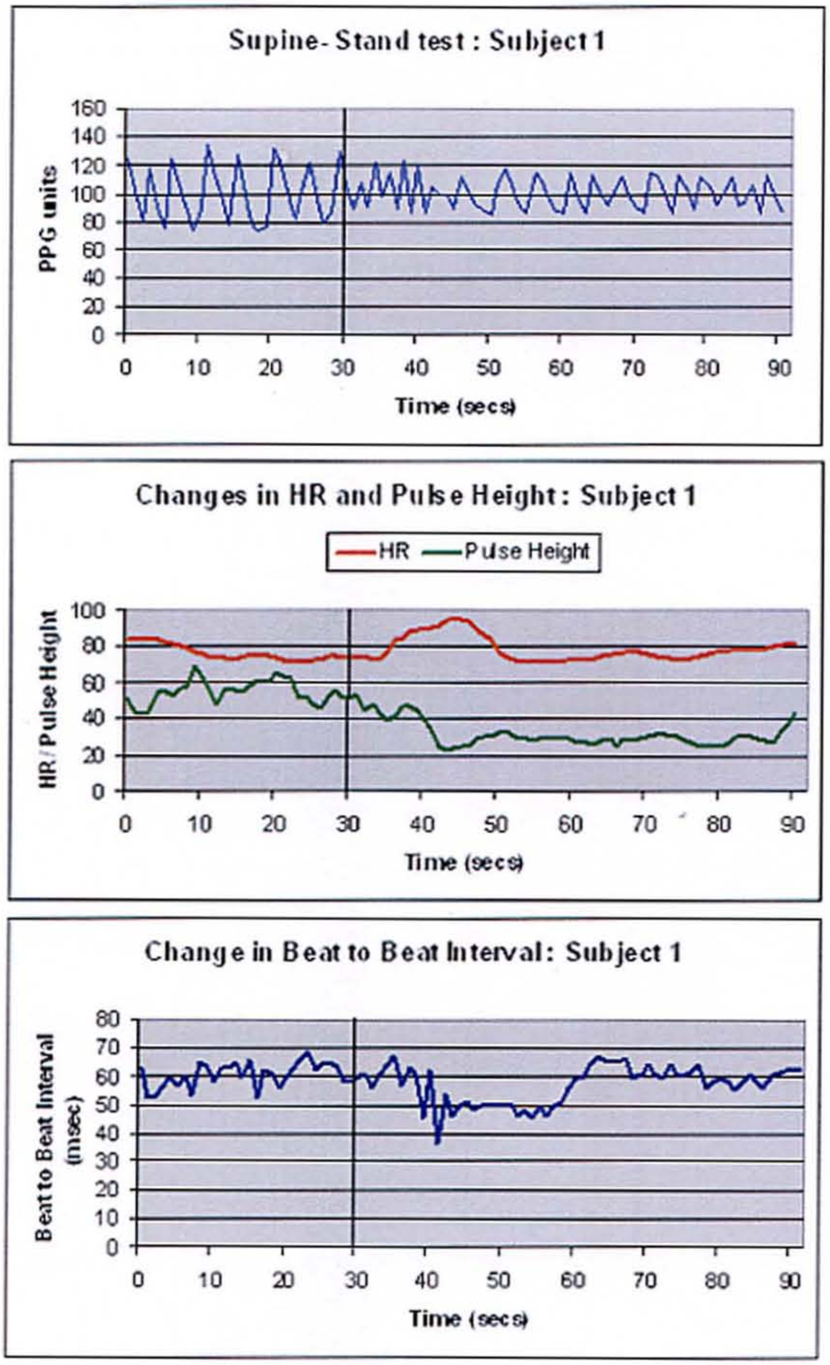


Figure 4.21 Results of supine stand test of subject 1.

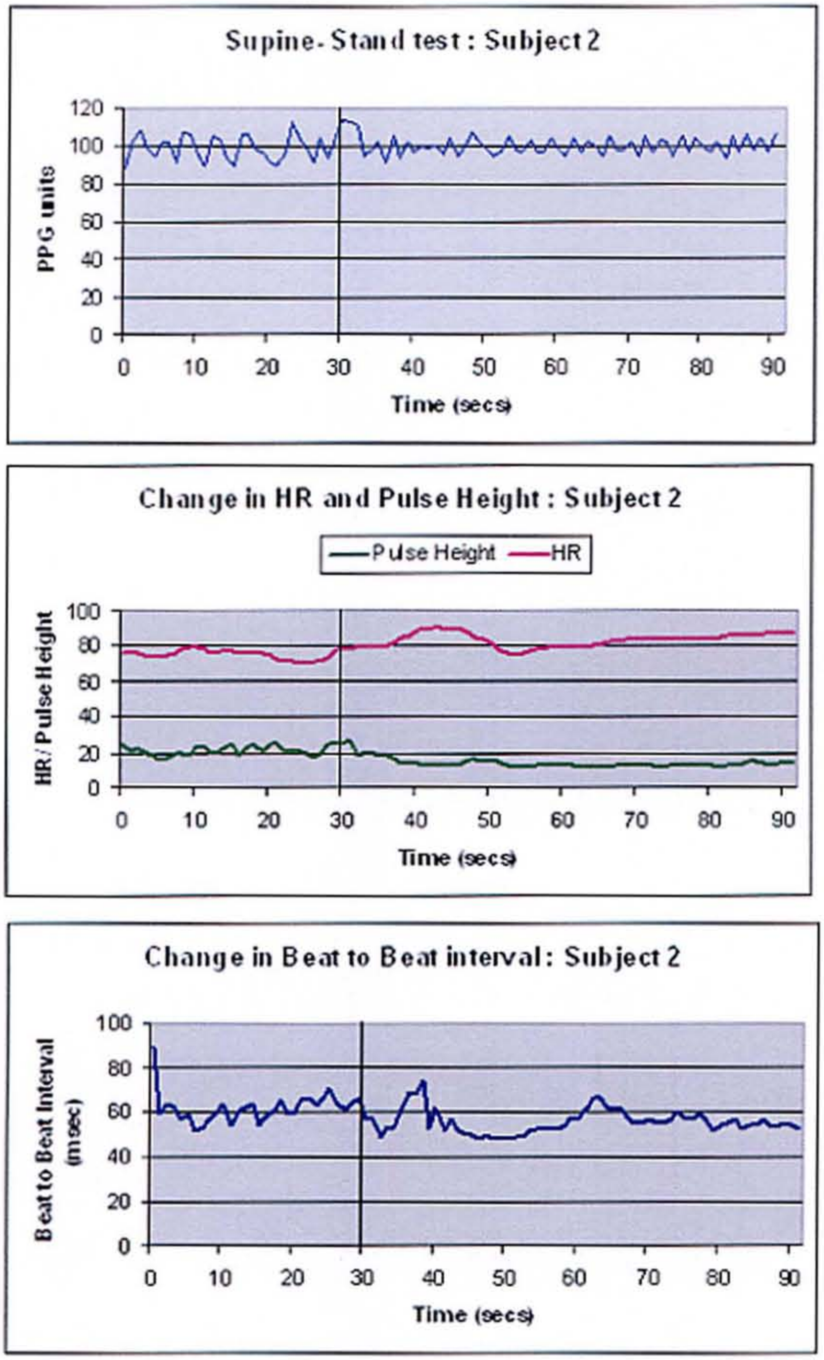


Figure 4.22 Results of supine stand test performed by subject 2.

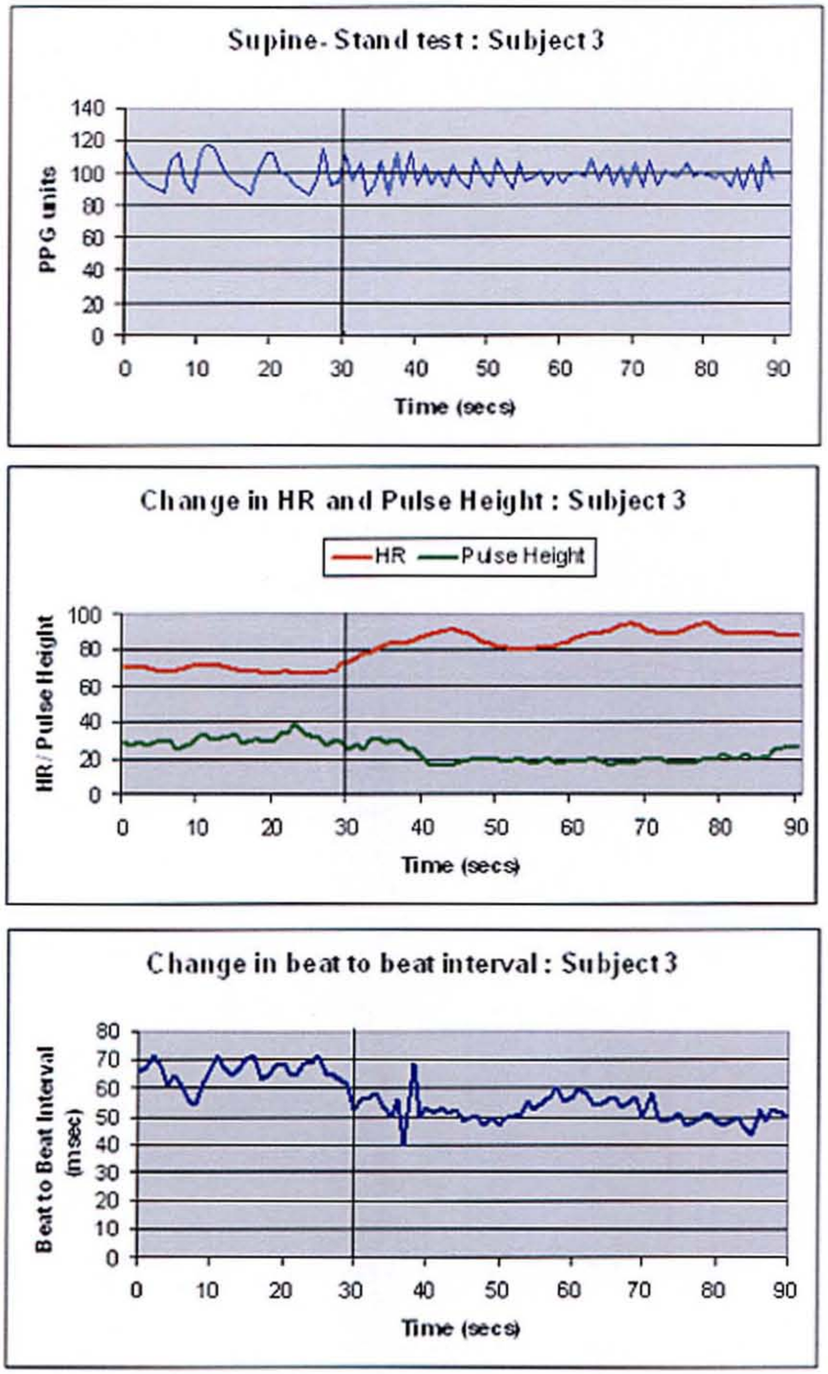


Figure 4.23 Results of supine stand test performed by subject 3.

Results from supine stand test show that there is a decrease in the blood flow as soon as the person stands up after 30 seconds. This can be seen from the plethysmograph data. It is also seen that a decrease in the blood flow decreases the pulse height of the PPG waveform and is accompanied by an increase in the heart rate. The beat to beat interval waveform also shows a decrease with an increase in the HR. These are in accordance with the expected data.

4.1.8 Bluetooth Pulse Oximeter Results

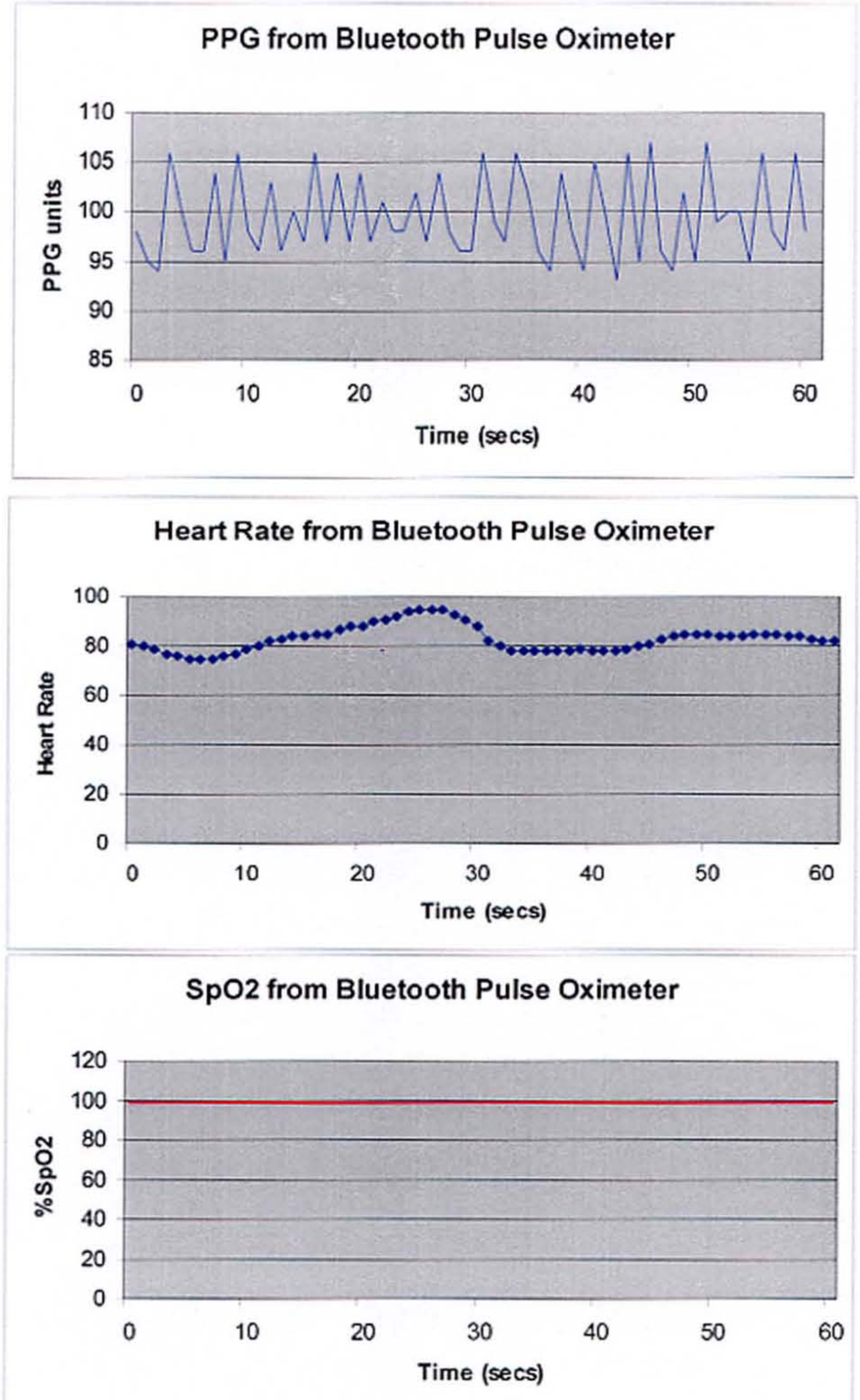


Figure 4.24 SpO_2, Heart Rate and PPG data of subject 1 from the Bluetooth Pulse Oximeter.

CHAPTER 5

CONCLUSION

The main aim of this project was to develop an ambulatory device that can monitor the heart rate, SpO_2 and the plethysmograph waveform and to develop a software program that would acquire, display and store the data. Once the software program was developed the goal was to compare the finger, ear and the reflectance sensor under different movements and to conclude on which would be the suggested choice for the desired application. Based on the goals that were originally set this project was a successful one. I developed a system that would monitor the heart rate, SpO_2 and the PPG of a person and collected the data and compared the three sensors. I also developed software for Bluetooth Pulse Oximeter to send data with the help of Bluetooth technology.

To conclude from the comparative tests of the sensors, it was observed that different sensors worked well with different movements. Considering the hand movements the preferred choice of sensor would be an Ear Sensor or a Reflectance Sensor. Finger Sensor showed the least SNR and was thus not preferred with hand movements. With head movements, Finger Sensor or an Ear Sensor was to be considered for the application. It was assumed that the Reflectance Sensor would move if not held properly at the forehead, due to head movements and thus showed a lot of motion artifacts. Results from the body movements suggest that an Ear Sensor would work well. It was also a good habit to consider the low perfusion at the ear site with respect to some people during these applications. Considering the heart rate monitoring with motion a Reflectance Sensor would work well for such an application and a Finger Sensor with SpO_2 monitoring with motion.

Expected changes as per the literature were observed in the PPG waveform under mental activity test and supine stand test.

Depending on the application for which a pulse oximeter is used and the parameter to measure one can select a sensor from this project and carry out their research. Thus this project serves as a guide in selecting among the sensors, depending on the applications and/or different conditions.

The ear sensor version of this project is now being applied in a research project at the VA Medical Center in an ambulatory project recording vital signs in first responder trainees.

CHAPTER 6

LIMITATIONS AND FUTURE DEVELOPMENTS

Limitations of a pulse oximeter include the inaccuracy of measuring the correct readings with abnormal hemoglobin such as the carboxyhemoglobin and met- hemoglobin. It may also be not accurate with the exposure of the measuring probe to ambient light. Nail polish or nail coverings with finger probe may affect the readings as well as the intravascular dyes [15]. These are also true for the PDA based Ambulatory Pulse Oximeter.

Making the entire system wireless by sending the data to the PDA with Wi-Fi technology which provides more range than the Bluetooth technology could also be one of the future developments.

APPENDIX A

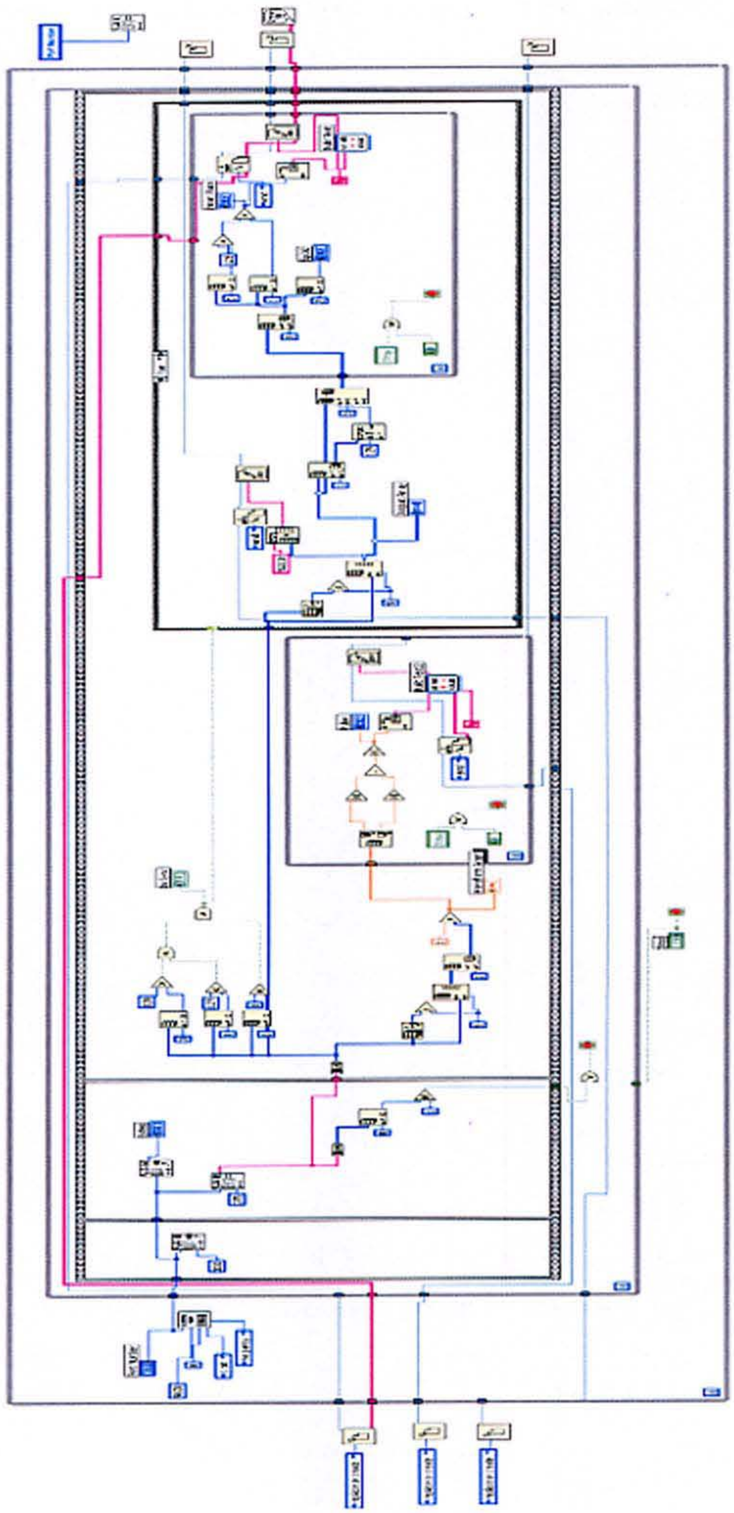
SPECIFICATIONS OF NONIN PULSE OXIMETER

The specifications of the Nonin Pulse Oximeter are as follows:

1. Oxygen Saturation Range: 0-100%
2. Pulse Rate Range: 18-300 pulses per minute.
3. Measurement Wavelengths: Red 660 nanometers, Infrared 910 nanometers.
4. Power Draw: 60mW.
5. Voltage Input: 2-6 volts dc operating.
6. Output digital signal: 0-5 volts.
7. Weight: 75g (including cable 6' and connector).
8. Plethysmographic pulse value: 0-254.
9. Status byte: 128-255
10. SpO_2: 0-100.
11. HR value bits 7&8 (128-511) 511= bad data and 0-6 bits (0-127).

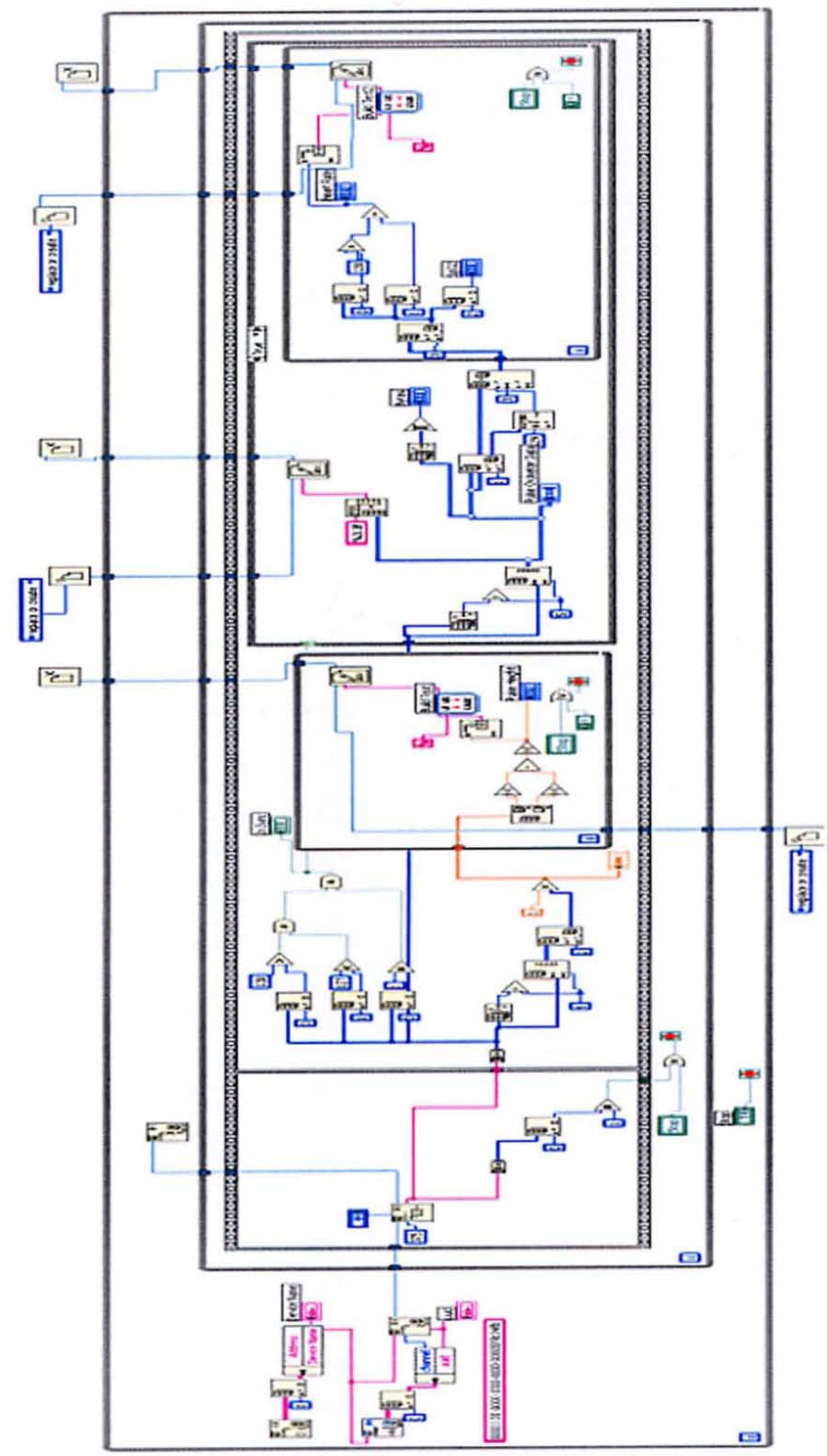
APPENDIX B

LABVIEW CODE FOR XPOD PULSE OXIMETER



APPENDIX C

LABVIEW CODE FOR BLUETOOTH PULSE OXIMETER



REFERENCES

[1] http://en.wikipedia.org/wiki/Vital_signs (April 2006)

[2] http://www.austincc.edu/~emeyerth/hemoglob.htm (March 2006)

[3] Suzanne M. Wendelken, Susan P McGrath, Metin Akay, George T. Blike: "Using A Forehead Reflectance Pulse Oximeter To Detect Changes In Sympathetic Tone," Engineering in Medicine and Biology Society, 2003, Proceedings of 25th Annual International Conference of the IEEE.

[4] Dave Hoff, Roy Zhang, Tad Stalter and Mike Carlson: "Pulse Oximetry."

[5] Y. Mendelson and R. A. Peura: "Noninvasive detection of profound arterial blood gases," IEEE Transactions on Biomedical Engineering, BME–31(12): 792–799, Dec 1984.

[6] Gail D. Baura: " Improved pulse oximetry in System Theory and Practical Applications of Biomedical Signals," Series in Biomedical Engineering, chapter 4, pages 66-85. IEEE Press, MA, 2002.

[7] Dr. Vijaylakshmi Kamat: "Pulse Oximetry," Indian J. Anaesth. 2002; 4 P6U (L4S) E: 2O6X1I-M26E8T

[8] T. L. Rusch, R. Sankar and J. E. Shcarf: " Signal processing methods for pulse oximetry," Computers in Biology and Medicine, 26(2):143-159, 1996.

[9] http://www.americanheart.org/presenter.jhtml?identifier=4701 (March 2006)

[10] Penugonda, Lakshmi Chitra: "Ambulatory biopotential measurement," Submitted to New Jersey Institute of Technology, May 2005.

[11] http://www.howstuffworks.com/ (March 2006)

[12] http://www.ni.com/ (March 2006)

[13] Suzanne M. Wendelken, a thesis: "Using a Forehead Reflectance Pulse Oximeter to Detect Changes in Sympathetic tone," Dartmouth College, New Hampshire, May 2004.

[14] http://www.cvphysiology.com/Blood%20Flow/BF005.htm (February 2006)

[15] http://www.rcjournal.com/online_resources/cpgs/pulsecpg.html (April 2006)

[16] http://www.hrvresearch.com/MedPond_HRV_Info.pdf (March 2006)

[17] Tomas Ward: "The Photoplethysmograph as an instrument for physiological measurement.," Department of Electronic Engineering, NUI Maynooth.

[18] http://nonin.com/ (April 2006)

[19] www.expansys.fr (April 2006)

[20] http://www.ebme.co.uk/arts/nellcor3.htm (April 2006)

[21] http://www.clinchem.org/cgi/content/full/51/2/434/F2 (April 2006)